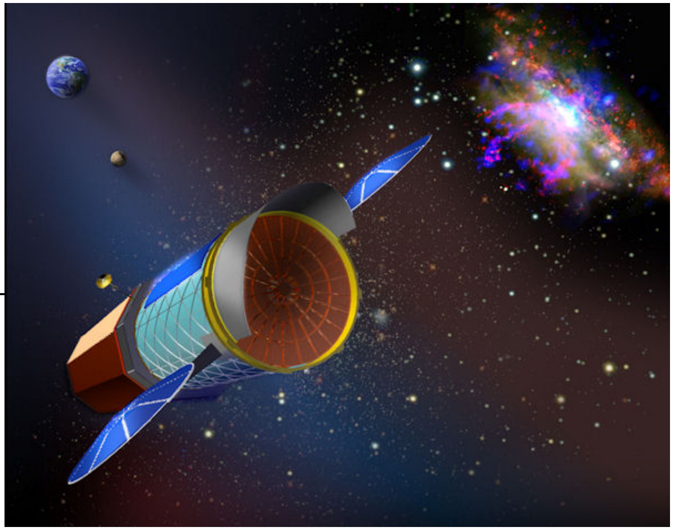
IXO Systems Definition Document
Chapter 1



Mission Overview

Precedence

- The present "IXO Systems Definition Document" constitutes the CONTROLLING DOCUMENT that defines the official baseline of the Systems Configuration for the NASA concept of the International X-ray Observatory
  - The "IXO Systems Definition Document" consists of nine Chapters.
  - The Appendix on payload elements contains our current assumptions regarding payload interfaces.

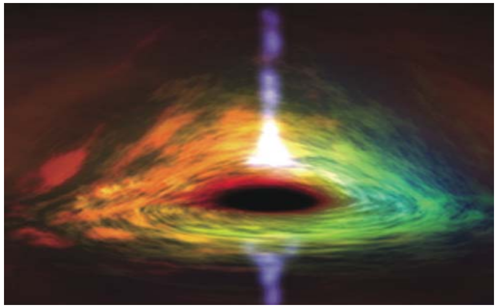
Credits

Credits for the IXO NASA engineering concept go primarily to:

- The IXO NASA/SAO Systems Engineering Team, whose members are:
  - Gabe Karpati, Mission Systems Engineer
  - Tony Nicoletti, Associate Mission Systems Engineer
  - Tom Buckler, Instrument Systems Engineer / Project Engineer
  - Mark Freeman, Optical Mission Systems Engineer
  - Dave Robinson, Lead Mechanical Systems Engineer
- IXO NASA Project Management
  - Jean Grady, et al.
- IXO NASA/SAO Science Team
  - Nick White, Harvey Tannenbaum, Jay Bookbinder, Paul Reid, et al.
- Members of previous Constellation-X Systems Teams
  - Jeff Stewart, et al.
- The members of the GSFC Integrated Design Center
  - Supporting numerous Constellation-X and IXO studies
- And numerous other engineers at GSFC, SAO, and various industry partners

Science Investigations Highlights

IXO Science Objectives



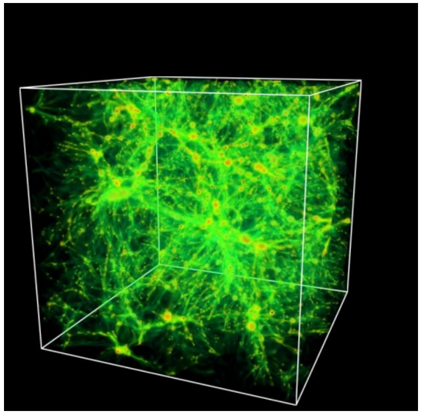
Black Hole growth and matter under extreme conditions

How do super-massive Black Holes grow and evolve?

What is the behavior of matter orbiting close to a Black Hole event horizons and does it follow the predictions of GR?

What is the equation of state of matter in Neutron Stars?

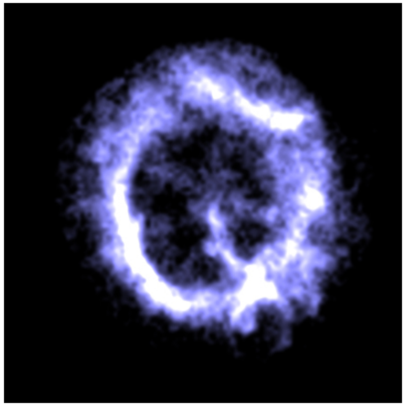
Galaxy Clusters, Galaxy Formation and Cosmic Feedback



What are the processes by which galaxy clusters evolve and how do clusters constrain the nature of Dark Matter and Dark Energy?

How does Cosmic Feedback work and influence galaxy formation?

Are the missing baryons in the local Universe in the Cosmic Web and if so, how were they heated and infused with metals?



The life cycles of matter and energy

How do supernovae explode and create the iron group elements?

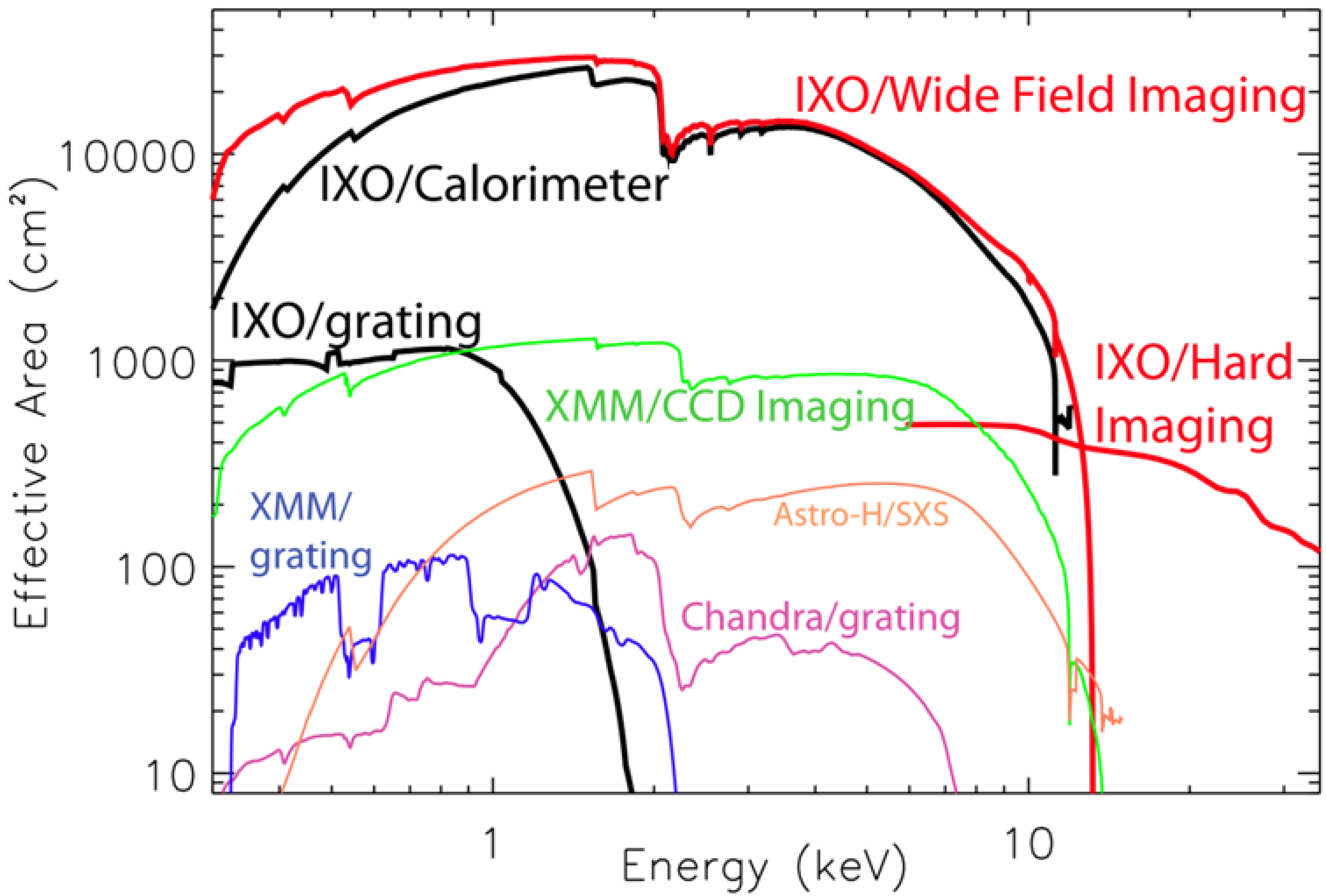
How do high energy processes affect planetary formation and habitability?

How are particles accelerated to extreme energies producing shocks, jets and cosmic rays?

Astronomy Science Objectives → Payload Performance Requirements

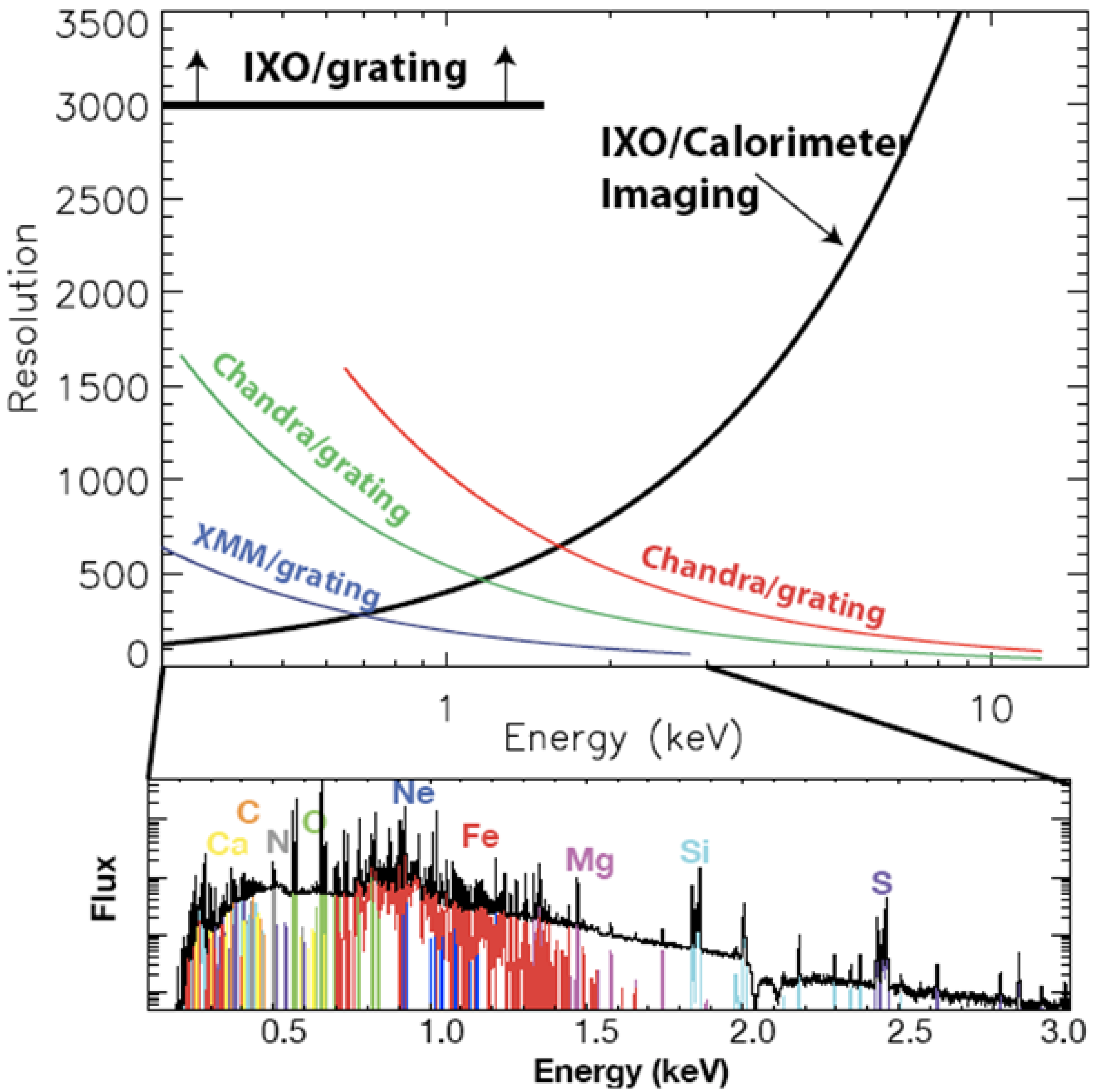
Black Hole evolution Strong gravity Strong gravity Missing Baryons	Mirror Effective Area	3 m^2 @1.25 keV 0.65 m^2 @ 6 keV 150 cm^2 @ 30 keV 1000 cm^2 (0.3 – 1 keV)
Black Hole evolution Black Hole evolution Large scale structure Missing baryons Strong Gravity	Spectral Resolution (FWHM), over FOV, over band	Δ E = 2.5 eV, 2x2’, (0.3 - 7 keV) Δ E = 10 eV, 5x5’, (0.3 - 7 keV) Δ E =150 eV, 18’, (0.1 - 15 keV) E/ Δ E = 3000, (0.3 - 1 keV) Δ E = 1 keV, 8x8’, (10 – 40 keV)
Cosmic Feedback Black Hole evolution	Angular Resolution	$\leq$5 arc sec HPD (0.1 – 7 keV) 30 arc sec HPD (7 - 40 keV)
Strong gravity, EOS	Count Rate	1 Crab with >90% throughput. Δ E < 150 eV @ 6 keV (0.1 – 15 keV)
AGN geometry, strong gravity	Polarimetry	1% MDP on 1 mCrab,100 ksec, 3 σ , 2 - 6 keV
Black hole evolution	Astrometry	1 arcsec at 3 σ confidence
Neutron star studies	Absolute Timing	50 μ sec

Mirror Effective Area



Spectral Capability

- The IXO energy band contains the K-line transitions of 25 elements Carbon through Zinc allowing simultaneous direct abundance determinations using line-to-continuum ratios, plasma diagnostics and at iron K bulk velocities of 200 km/s



Science Observations with Five Instruments

Five Instruments

- On-axis (on Movable Instrument Platform): XMS, WFI/HXI, HTRS, X-Pol
- Off axis (on Fixed Instrument: Platform): XGS

Four Science Modes

- One Science Mode for each MIP instrument
- XGS operates during all Science Modes
- Instruments that are not conducting science are in Standby

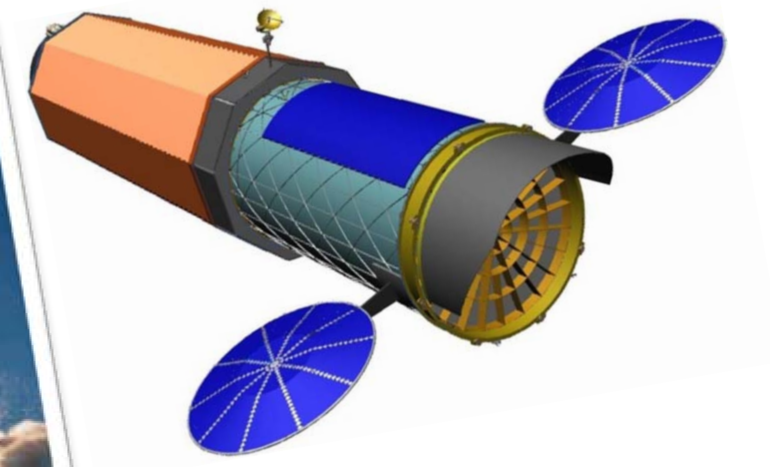
Field of Regard	▪ Pitch: +/- 20° ▪ Yaw: +/- 180° ▪ Roll: +/- 10° (with a goal of 20°)
Slew	▪ Average slew: 60 degrees in 60 minutes ▪ Average # of slews per day: 2.5 during first year of mission, less later
Operational Efficiency	▪ 85% average over the mission life
Timing accuracy	▪ Photon arrival tagged to UTC to ±100 μsec

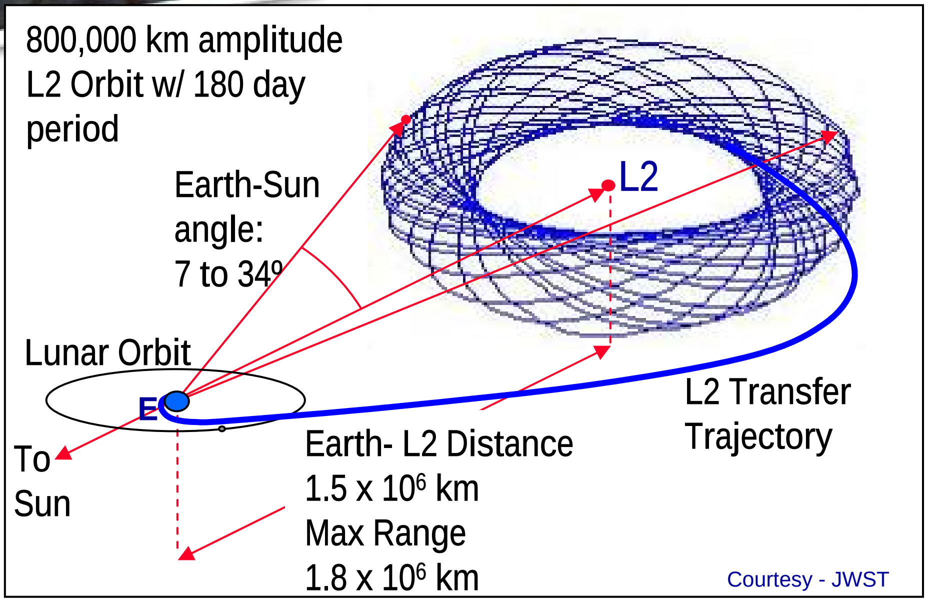
		Science Modes			
		Mode 1	Mode 2	Mode 3	Mode 4
Instrument Operations	Science	XMS, XGS	WFI/HXI, XGS	X-Pol, XGS	HTRS, XGS
	Standby	WFI/HXI, X-Pol, HTRS	XMS, X-Pol, HTRS	WFI/HXI, HTRS, XMS	WFI/HXI, XMS, X-Pol
% time		40%	40%	10%	10%
Observation Duration	Average	10 hours			
	Minimum	30 minutes			
	Peak	48 hours			

Mission Overview

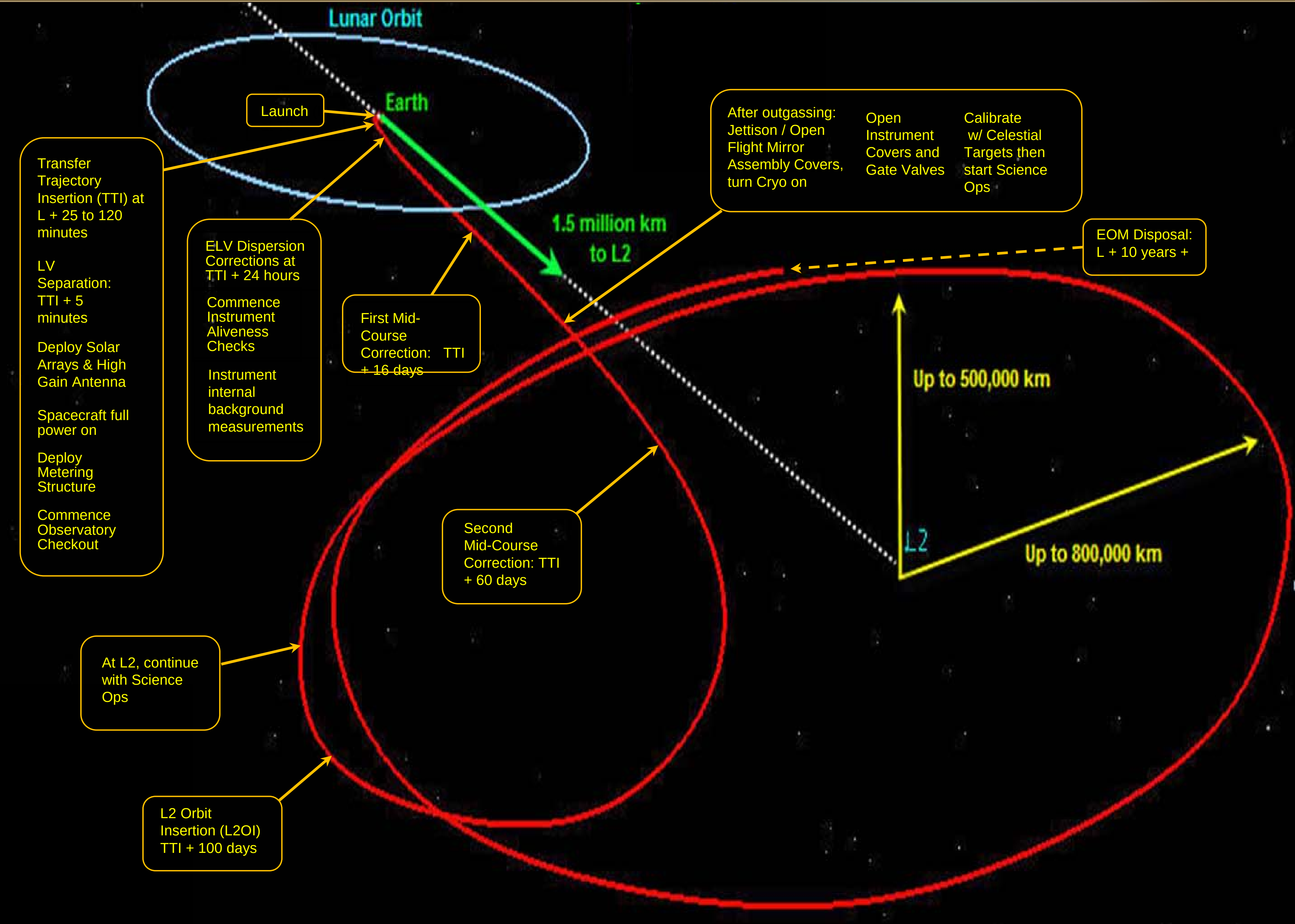
IXO Mission

- International Collaboration
  - NASA, ESA, JAXA
- Payload
  - 3.3 m dia X-ray mirror
  - 20 m focal length w/ 12 m extensible metering structure
  - Five science instruments for imaging and spectroscopy
- Mission Life
  - 5 years required, 10 years goal, consumables sized for 10 years
- Launch
  - March 2021
  - EELV medium fairing or Ariane 5
  - Max Liftoff Mass: 6425
  - Direct launch into “zero Insertion delta-v” L2 orbit
  - 100 day cruise
- Orbit
  - L2 800,000 km semi-major axis halo orbit
  - 0% solar or lunar obscuration throughout 10 years

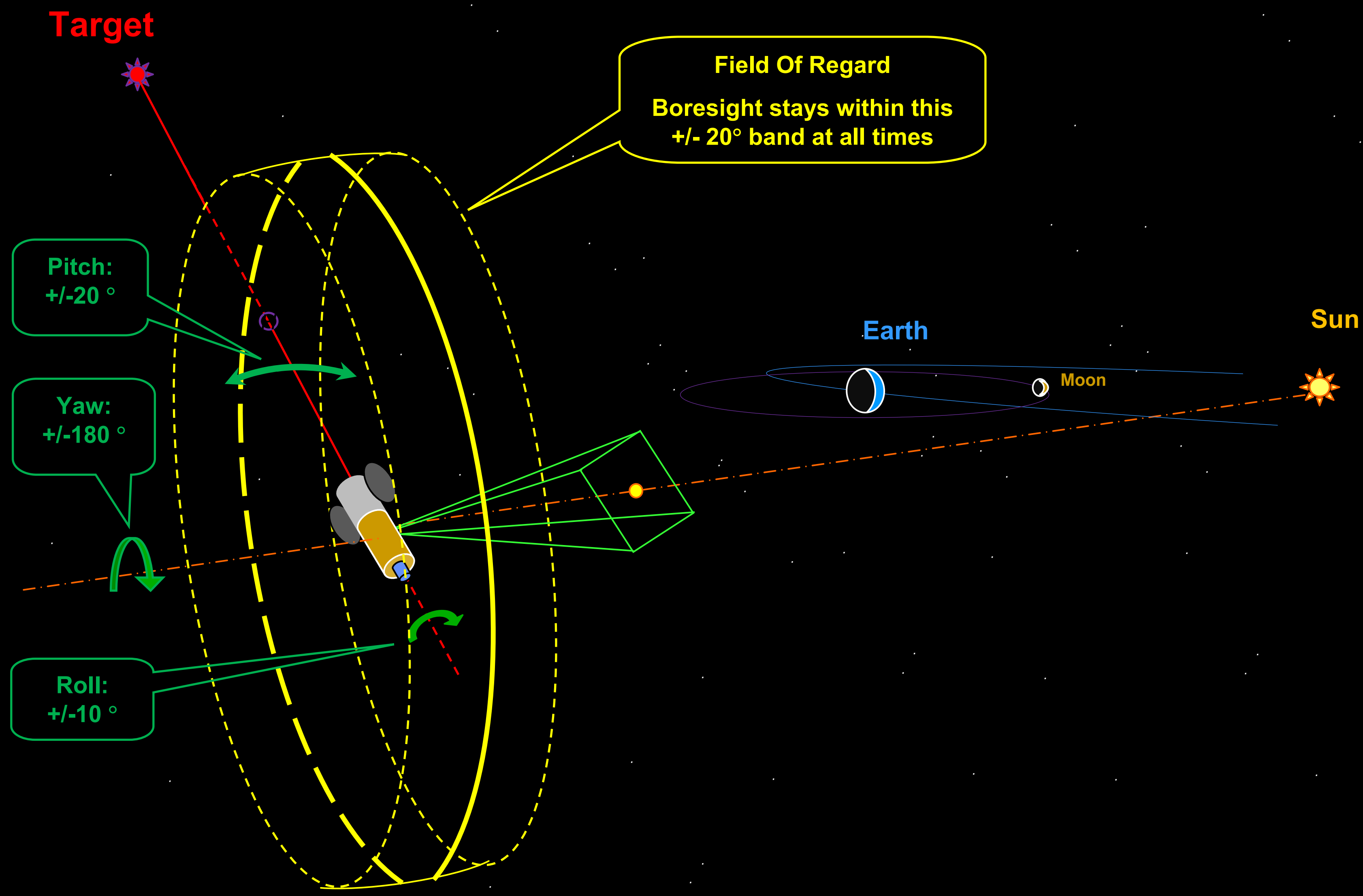




Mission Timeline



Field of Regard

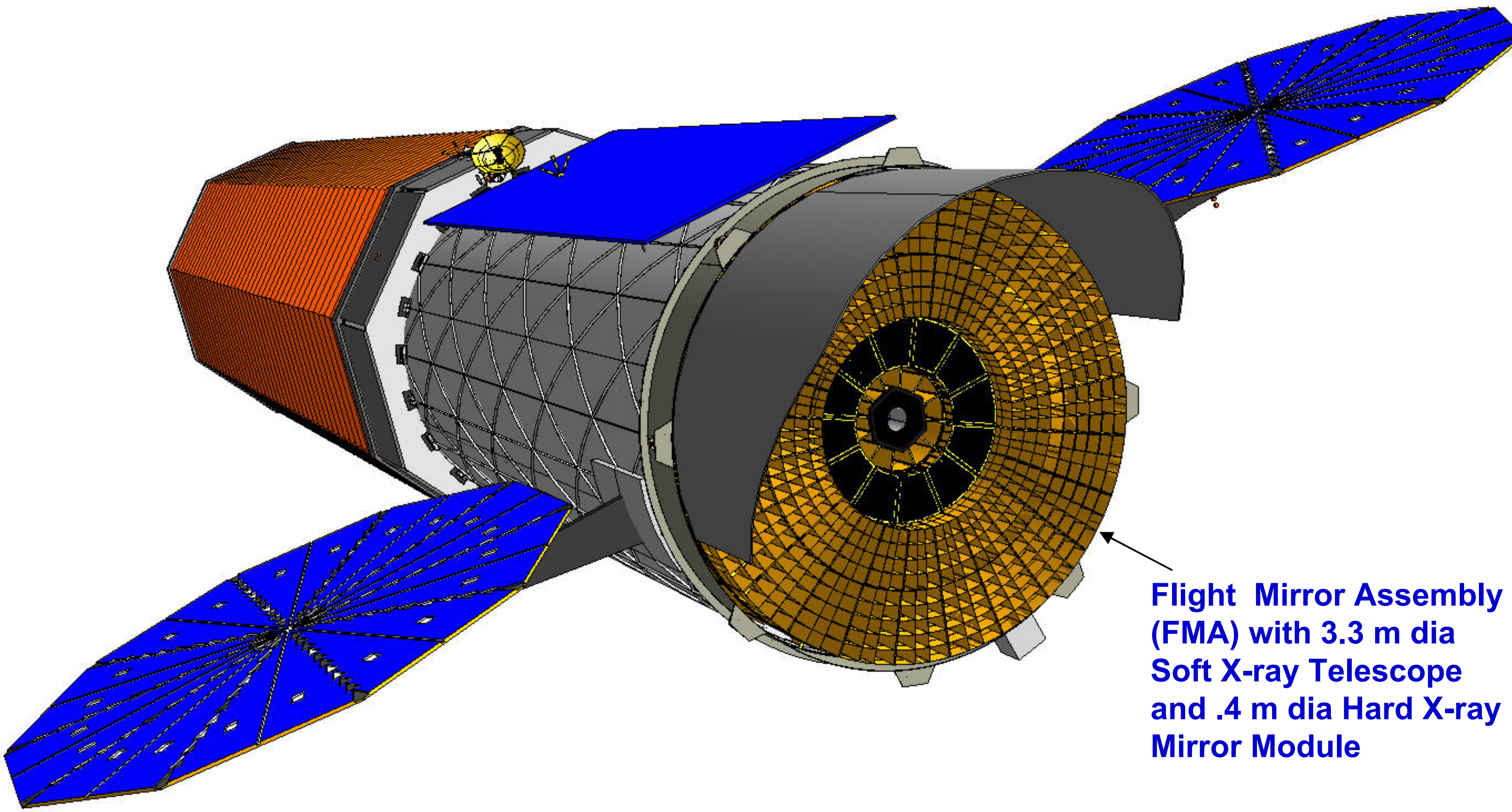


Operations Overview

- Launch
  - Launch opportunities exist every month of the year
  - Direct insertion into transfer orbit in full sun with continuous ground contact (have TDRSS capability)
  - Indefinite duration safe mode available immediately after LV separation
  - Deployments start right after LV separation
- Cruise to L2
  - 100 days total duration, starting with one month commissioning phase for checkouts, calibrations
  - Continuous DSN contacts during commissioning , then twice daily for 30 minutes for OD during cruise
  - Correction burns as required
  - Telescope covers deployed after observatory outgassing
  - Science observations may start during cruise
- L2 Insertion
  - Performed in fully deployed configuration (10^{-3} g level forces only)
- Nominal Mission Orbit
  - One daily 30 min DSN contact for downloads and OD, 21 days undisturbed orbits
  - Stationkeeping every 21 days, Reaction Wheel offloading as required during slews or during stationkeeping burns
  - Solar disturbance torque offloaded continuously real-time w/ mini-thrusters
- Observations
  - Pointing at a target for 10^3 to 10^6 seconds
  - 1 – 20 observations per week, repointing accomplished in less than an hour
  - Observing efficiency 85%
- EOL disposal
  - Passivate observatory, impart 1 m/s towards deep space (not required by NASA)
- Mission Ops
  - Highly autonomous observatory, 8 x 7 ground staffing
  - Chandra-like IXO Science and Operations Center integrates Mission Data System and Science Data System
  - Data latency 2 weeks required, 72 hours goal from completion of observation to product delivery, excludes bright source observations

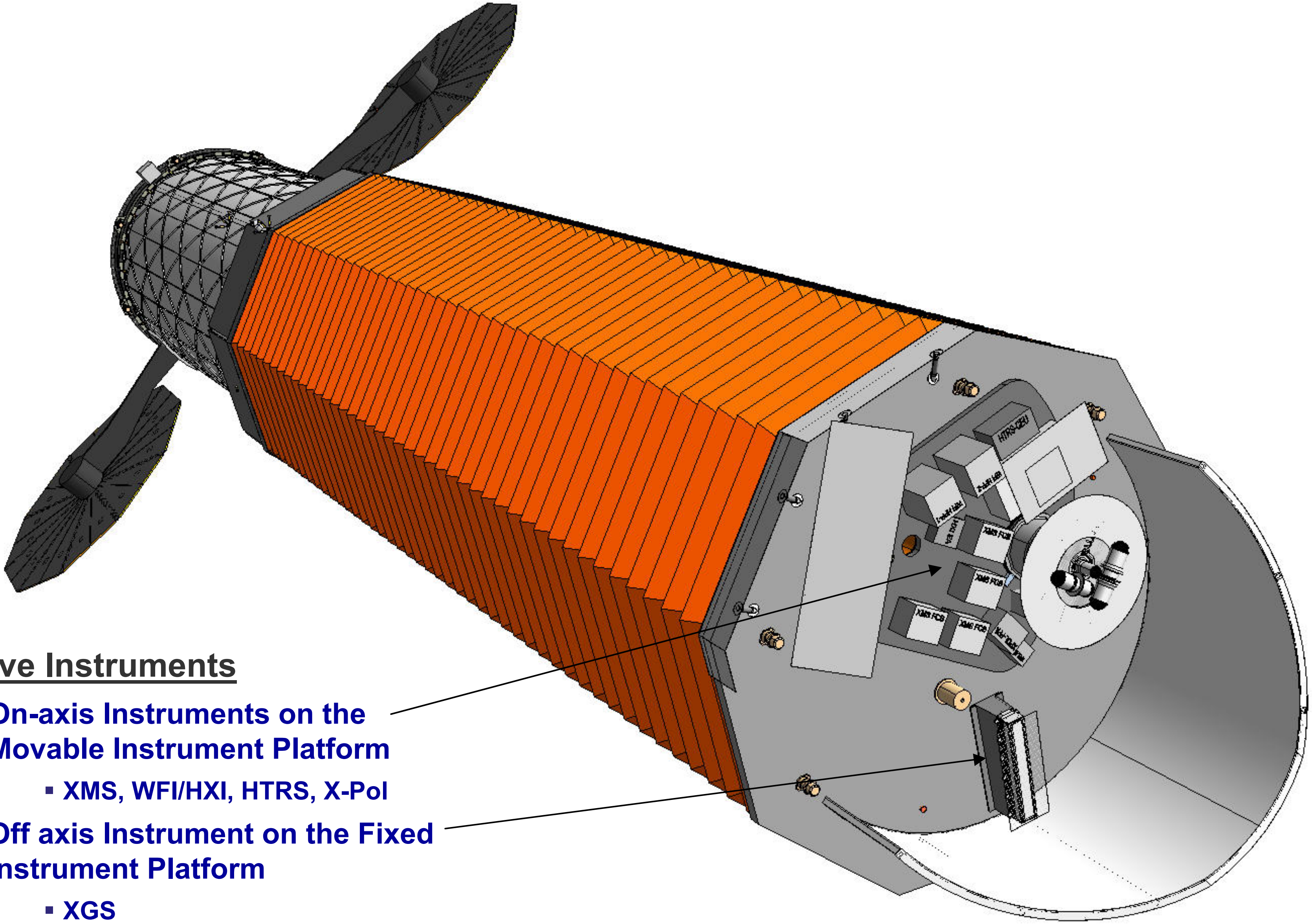
Observatory Configuration Overview

Observatory Fore View



Flight Mirror Assembly (FMA) with 3.3 m dia Soft X-ray Telescope and .4 m dia Hard X-ray Mirror Module

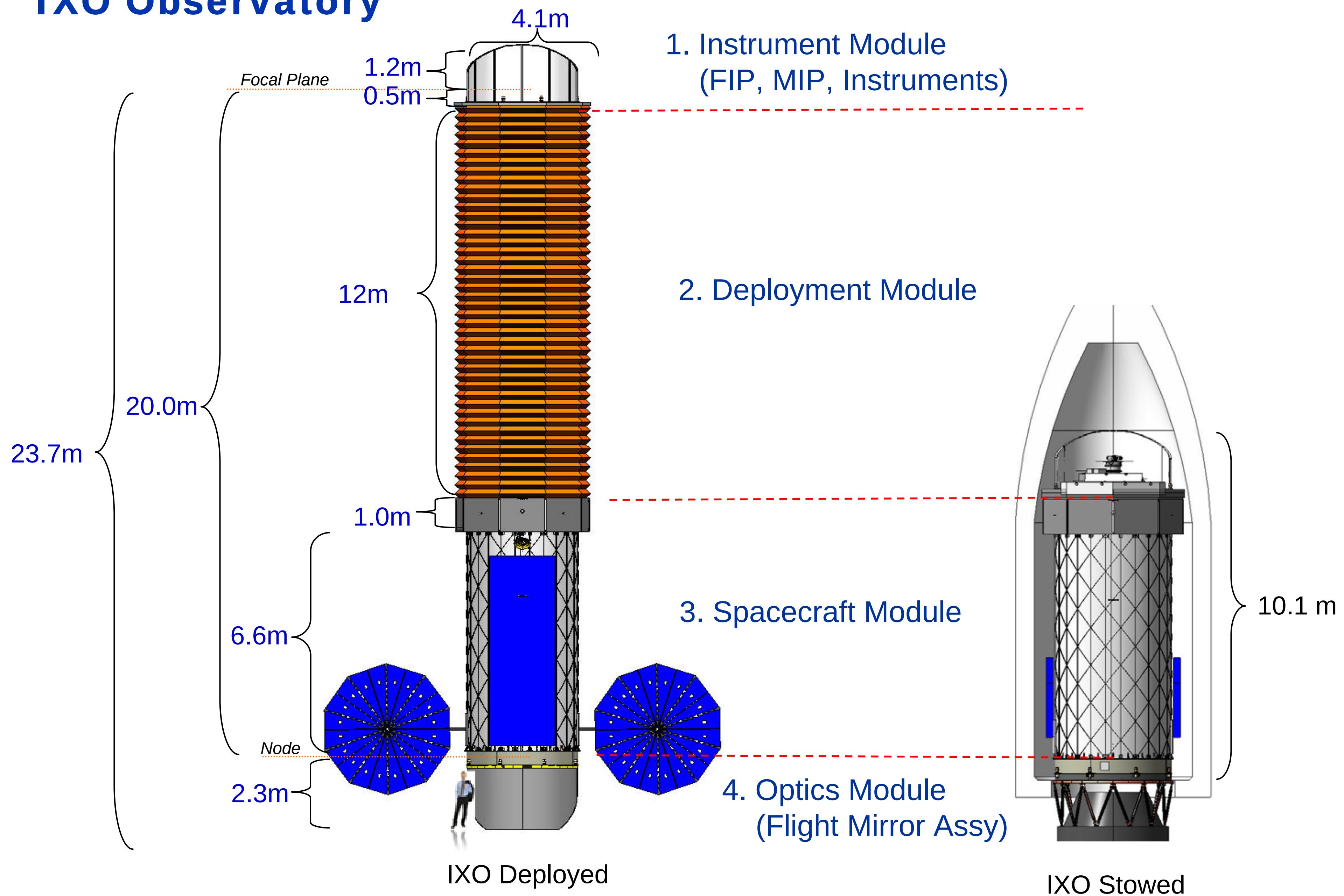
Observatory Aft View



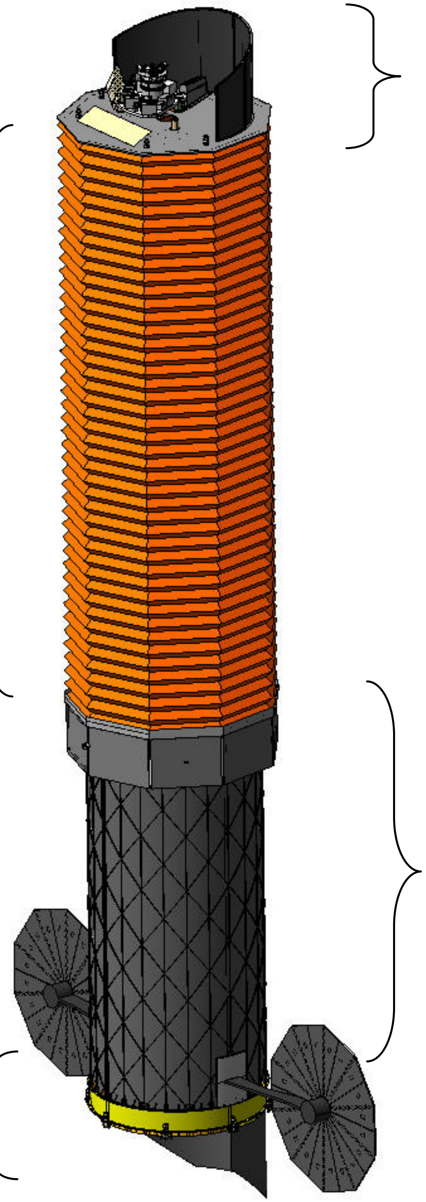
Five Instruments

- On-axis Instruments on the Movable Instrument Platform
  - XMS, WFI/HXI, HTRS, X-Pol
- Off axis Instrument on the Fixed Instrument Platform
  - XGS

IXO Observatory



Observatory Modules



Instrument Module

- Fixed Sunshade
- Moveable Instrument Platform (MIP) w/ four Instruments: XMS, WFI/HXI, X-POL, HTRS
- Fixed Instrument Platform (FIP) w/ fifth Instrument: XGS Camera

Deployment Module

- Three extensible ADAM-type masts with harness (not shown)
- 3.9 m diameter shroud, Whipple shield construction for micrometeoroid protection
- Two 3.5 m dia X-ray baffles

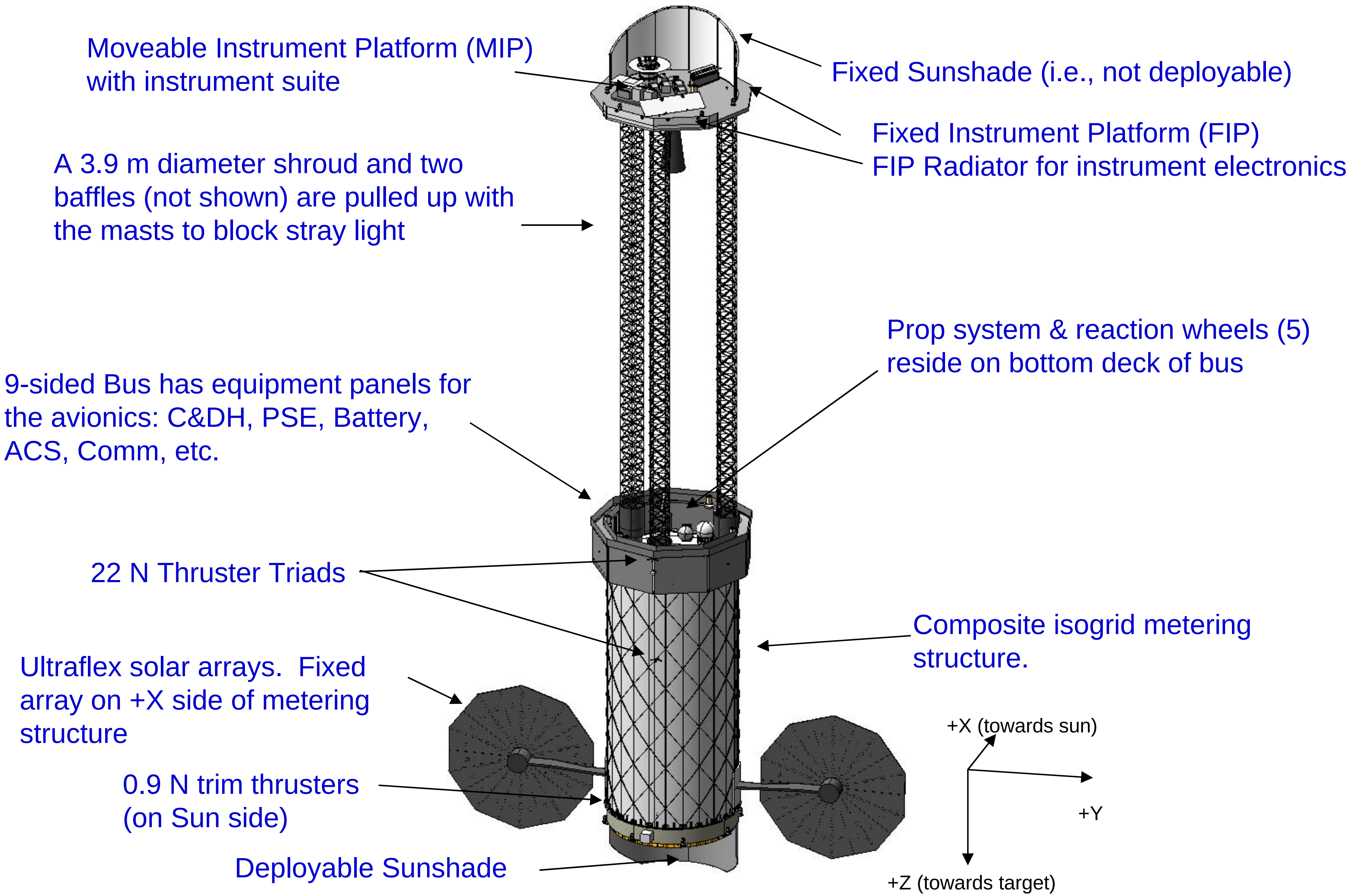
Spacecraft Module

- Nine sided S/C bus structure houses most hardware: avionics, power system electronics, battery, propulsion tanks, reaction wheels, etc.
- Composite isogrid metering structure / thrust tube
- High Gain Antenna
- 26 m^2 total body mounted and deployable non-articulated 3.4 m dia Ultraflex solar arrays
- Biprop and monoprop thrusters (14)

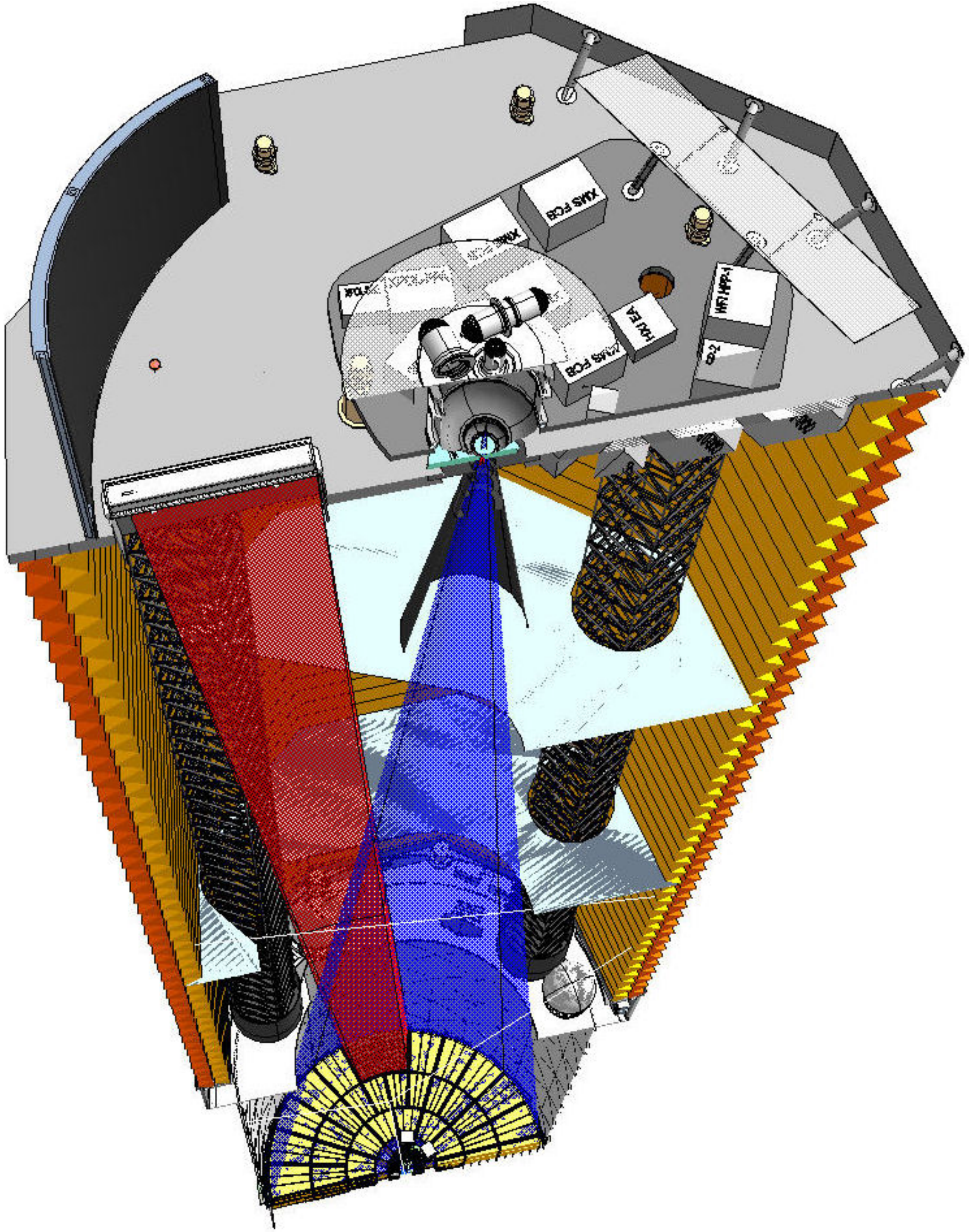
Optics Module

- Flight Mirror Assembly (FMA)
- FMA deployable outer and inner covers
- Deployable Sunshade
- TADS Fore Assy (Periscope)

Observatory Level Configuration Highlights

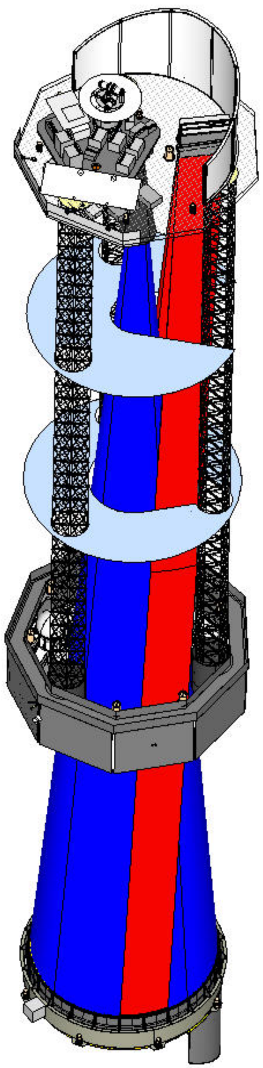


Observatory Cutaway View

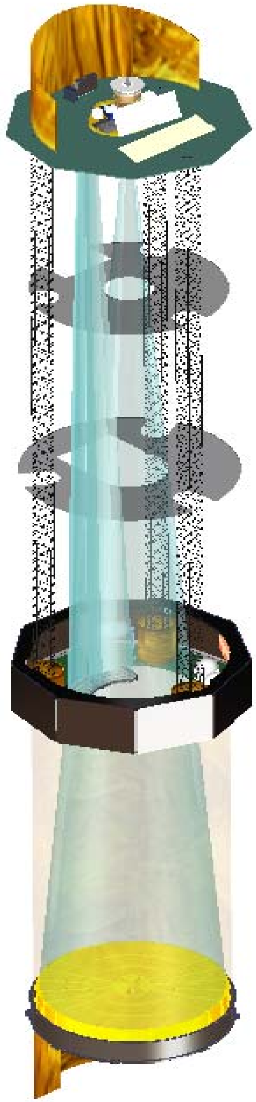


X-ray Beams and Baffles

- The X-ray traces of the FMA and XGS traverse nearly the entire length of the observatory
- Either Critical Angle Transmission Gratings (CAT) or Off-Plane Gratings (OP) XGS can be accommodated
- The x-ray beams drive the size, shape and placement of the spacecraft bus "ring"
  - Needs to be forward of the FMA for sufficient volume for bus components
  - Distance between the bus and the FMA limited to fit in the EELV medium fairing
  - (CG, mass propellant lines are additional considerations)



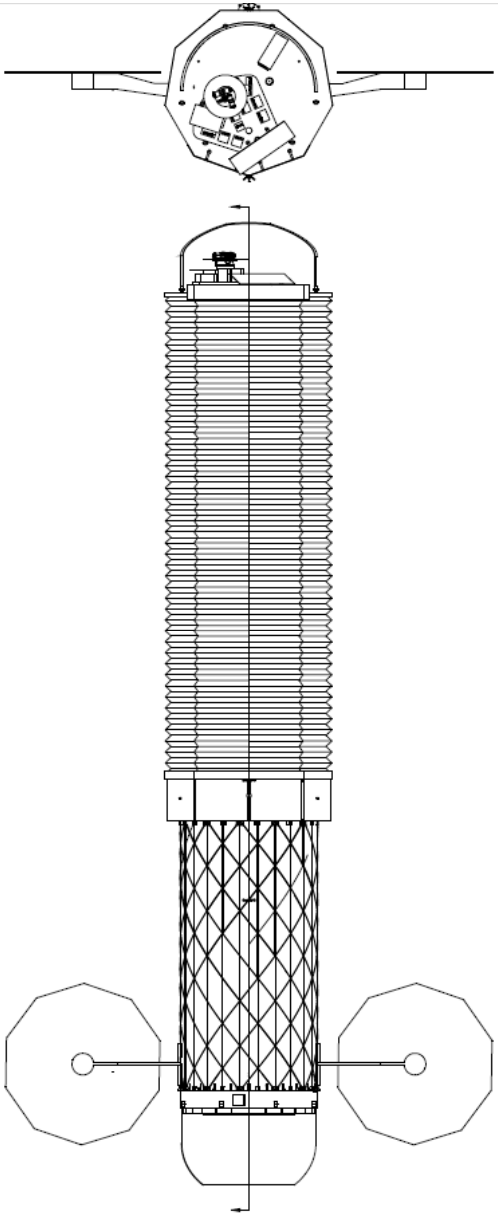
CATG XGS

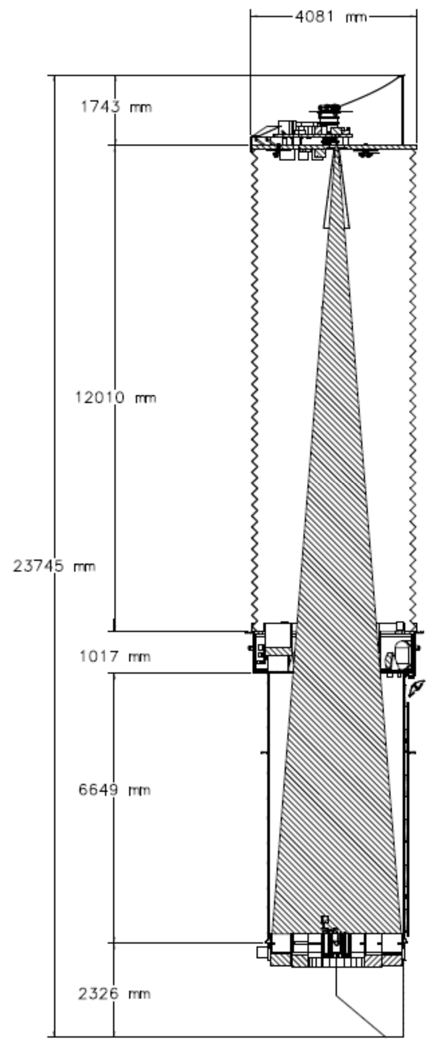


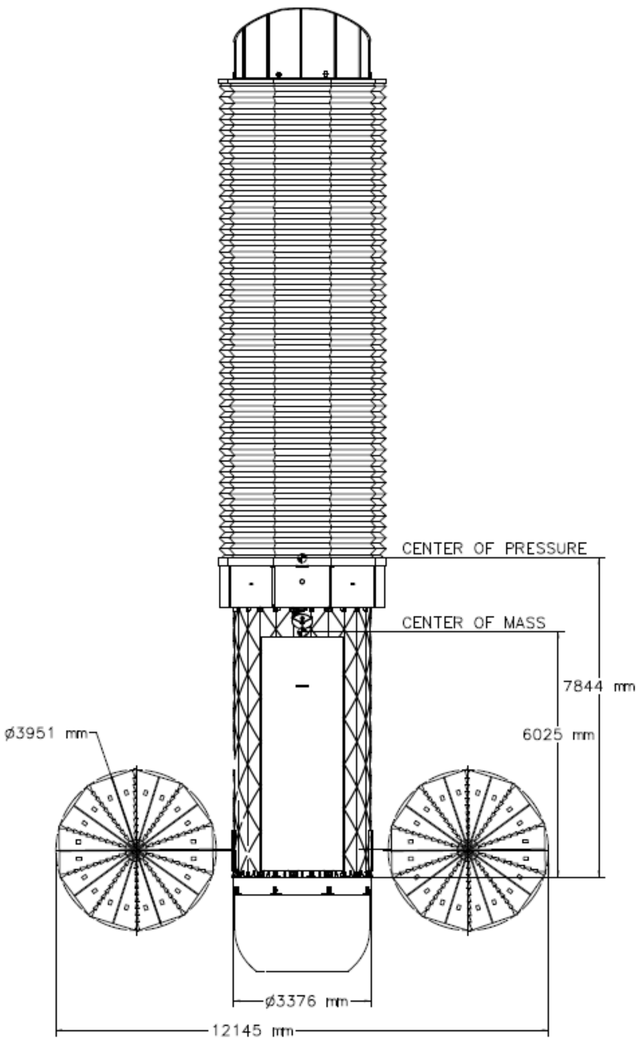
OP XGS

Observatory Deployed Configuration CP and CM

- CP at Z = - 7844 mm
- CM at Z = - 6025 mm
- CP / CM offset = 1819 mm

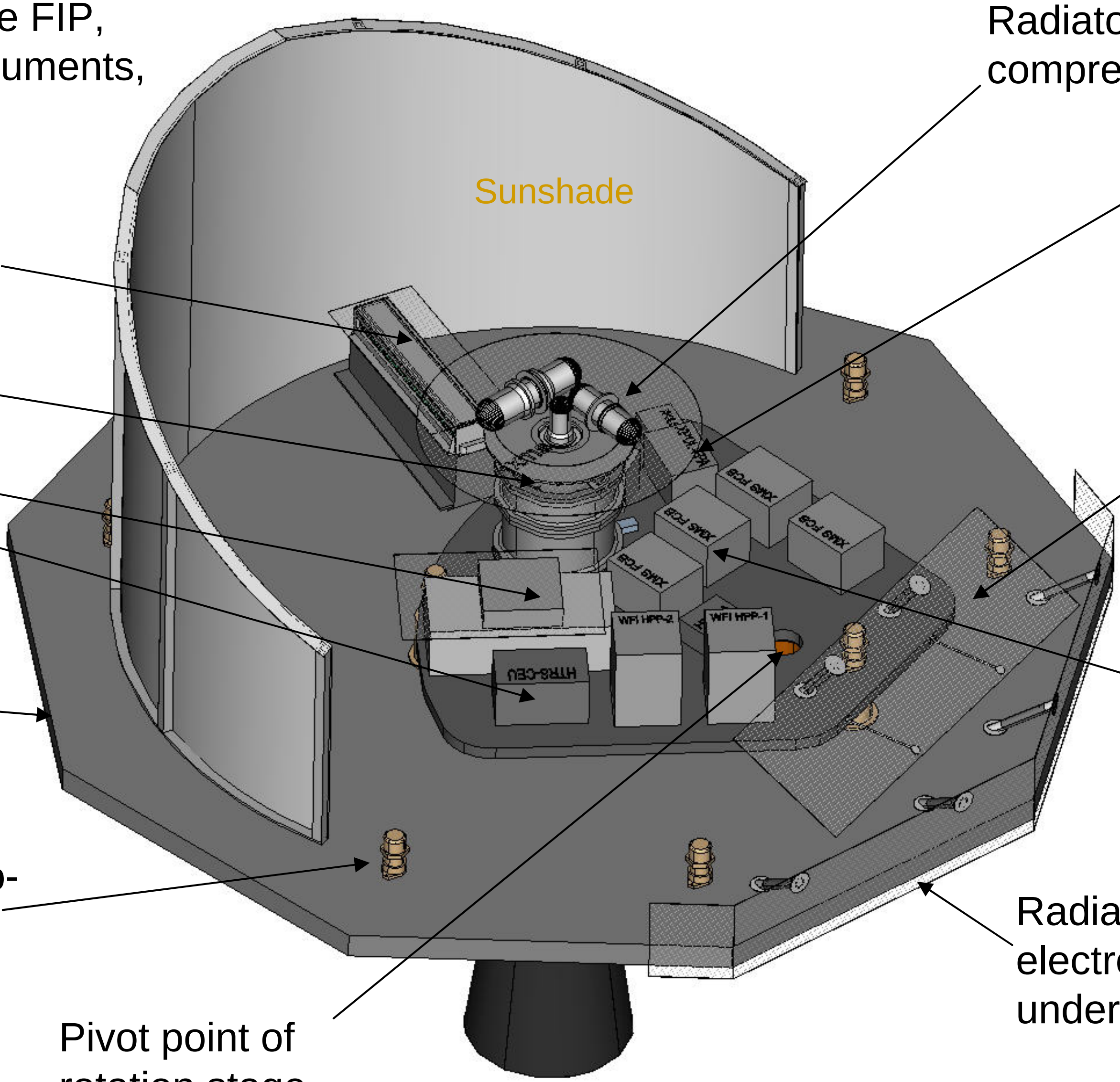




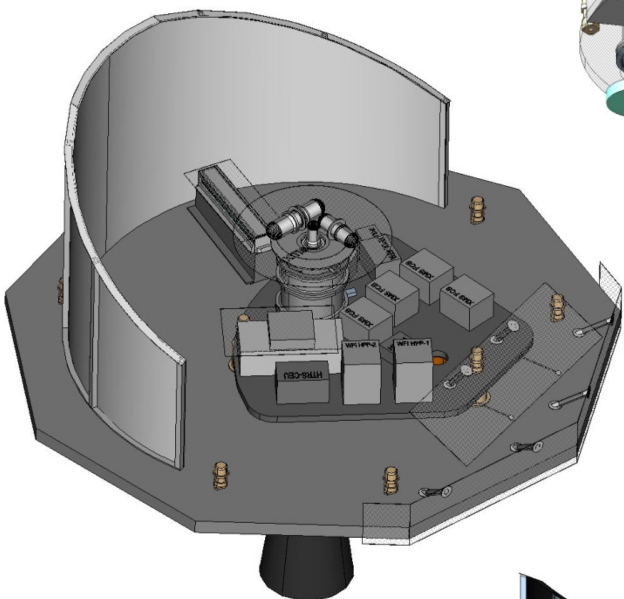


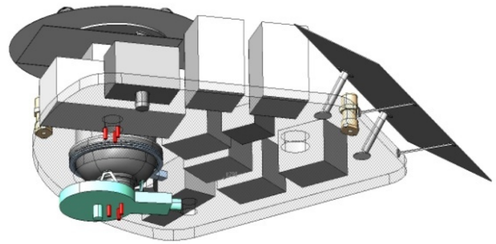
Instrument Module

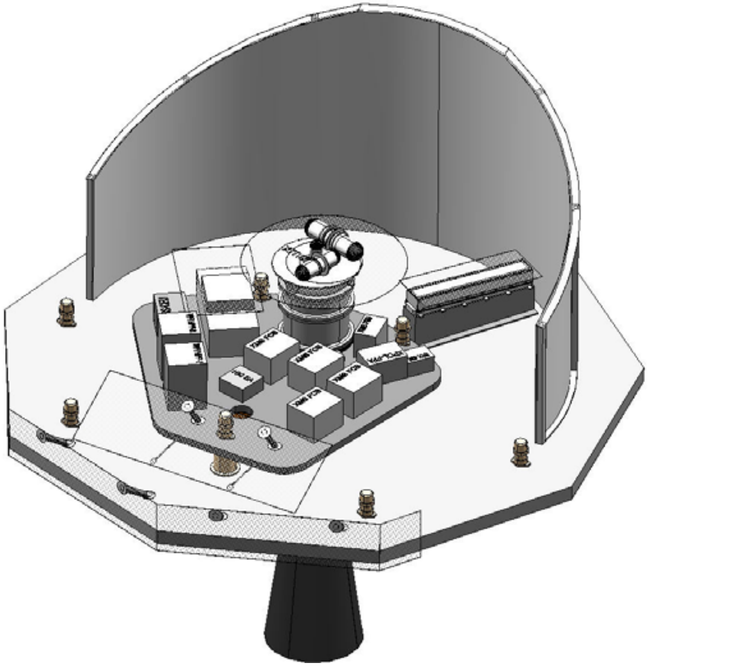
The IM consists of the FIP, MIP, Sunshade, Instruments, Electronics boxes

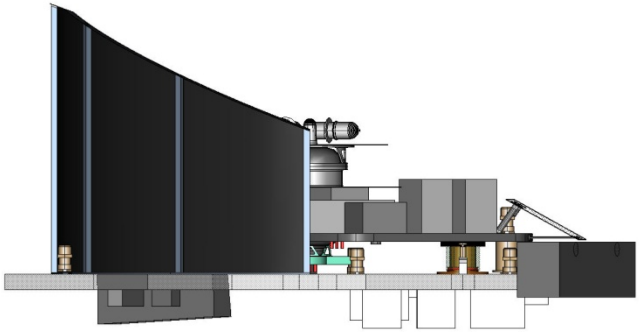


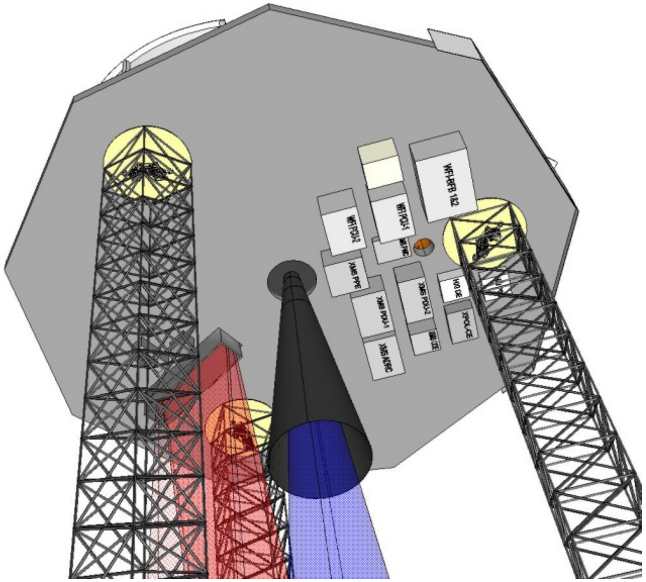
Instrument Module



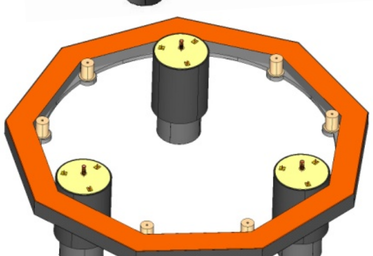


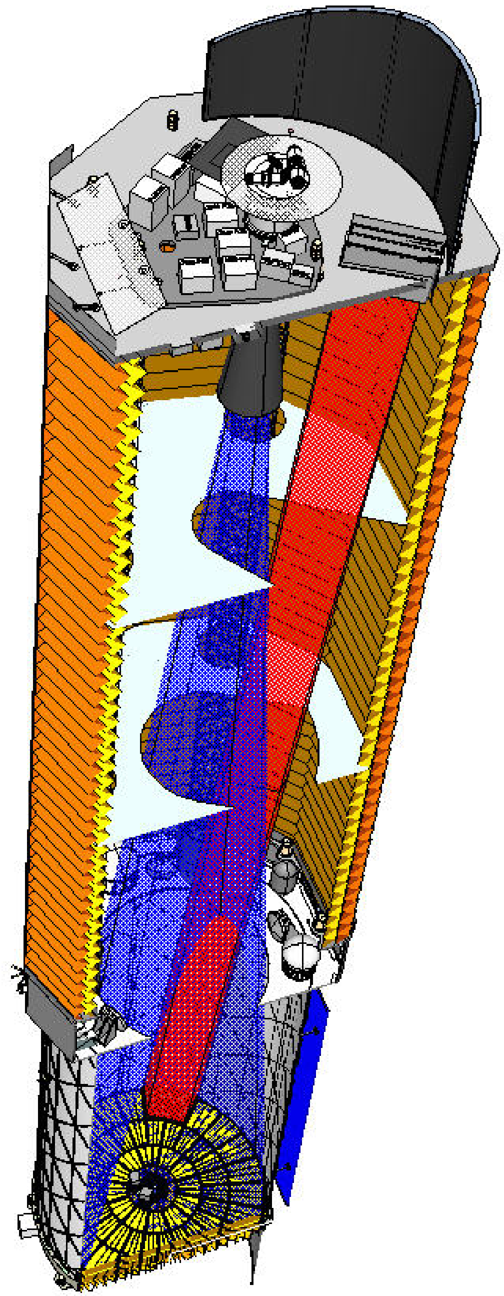


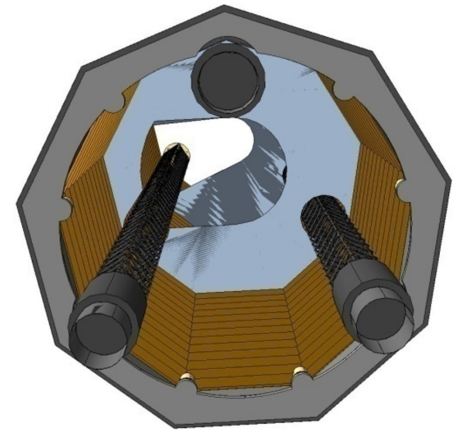


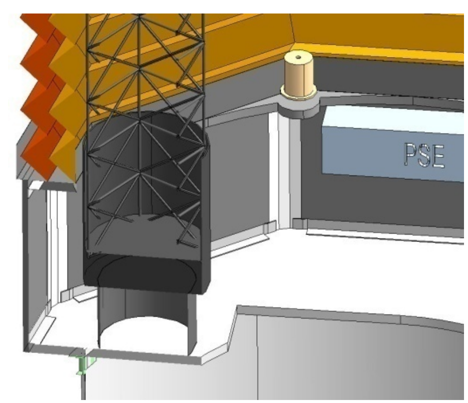


Deployment Module



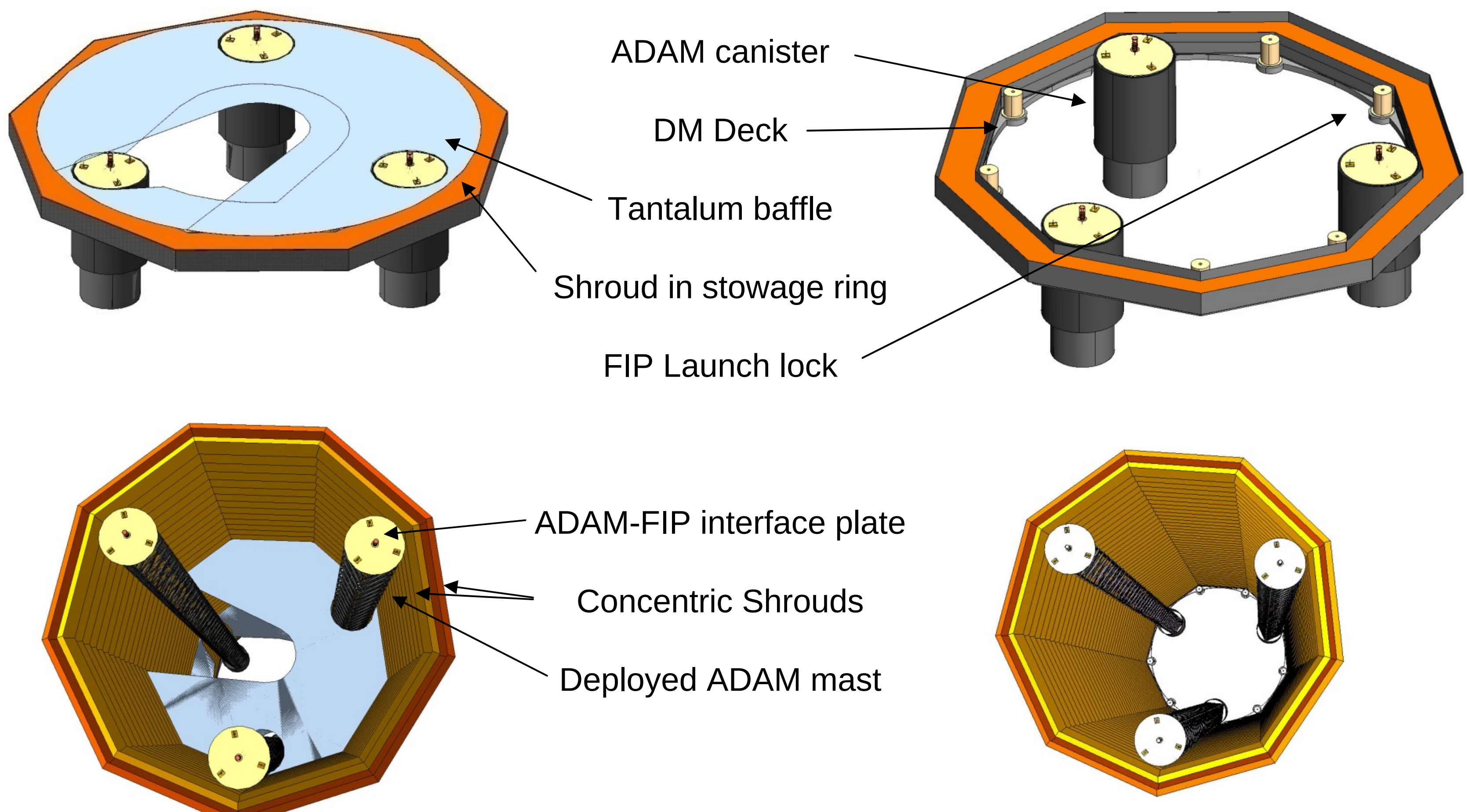






Deployment Module Implementation

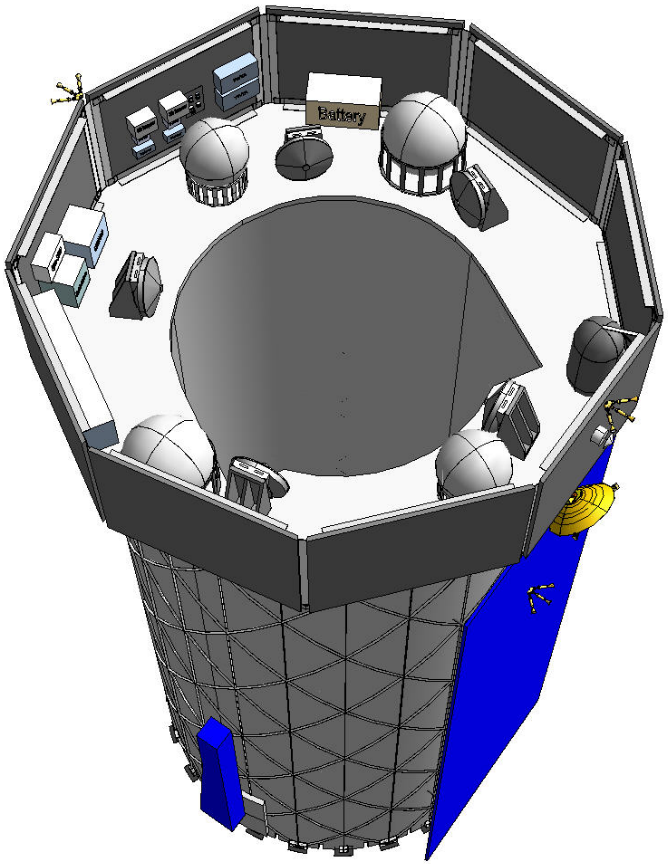
- Three ADAM masts deploy the IM a distance of 11.9 m
- Masts stow into canisters 65 cm diameter, 1m long
- Harness, shroud, and baffles are pulled up by the ADAM masts



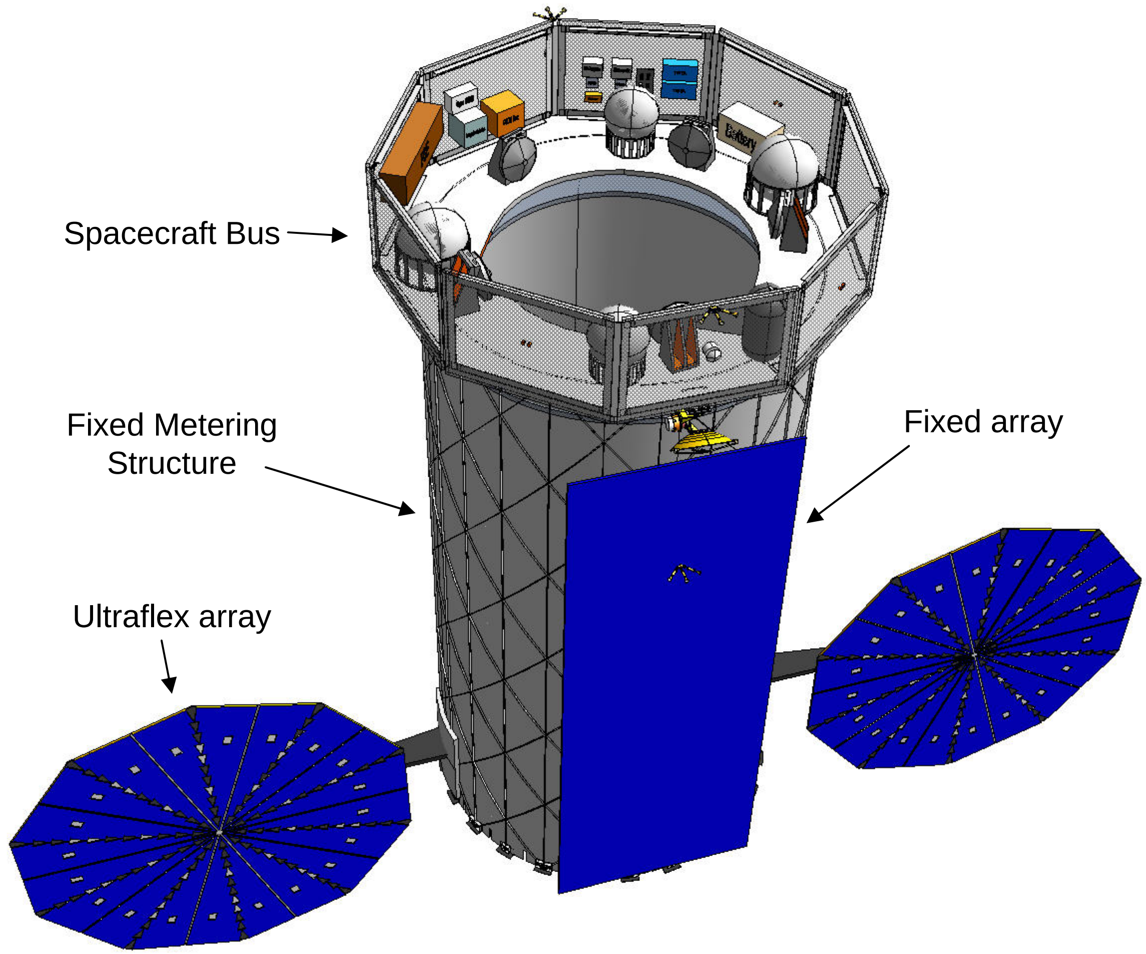
DM deployed, looking in +Z direction

DM deployed, baffles removed for clarity

Spacecraft Module Views



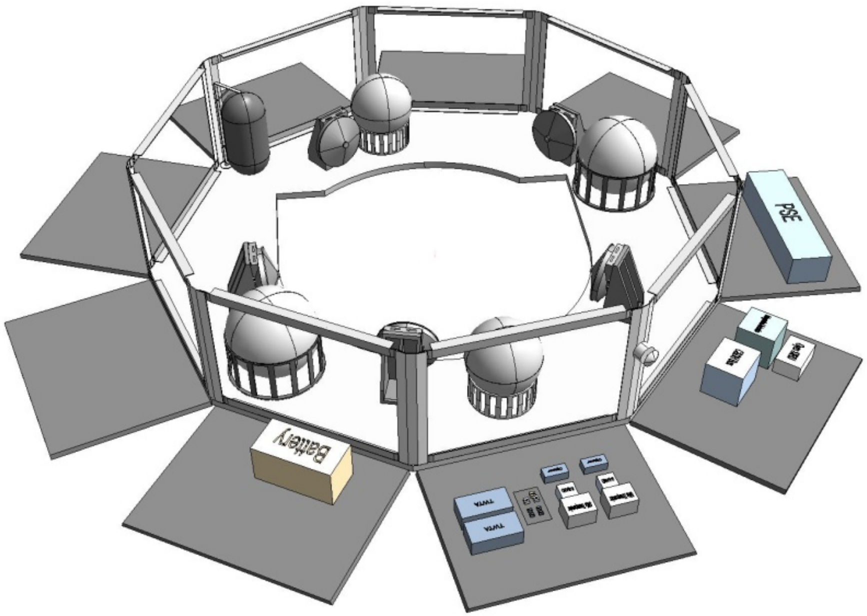
Stowed configuration



Deployed configuration

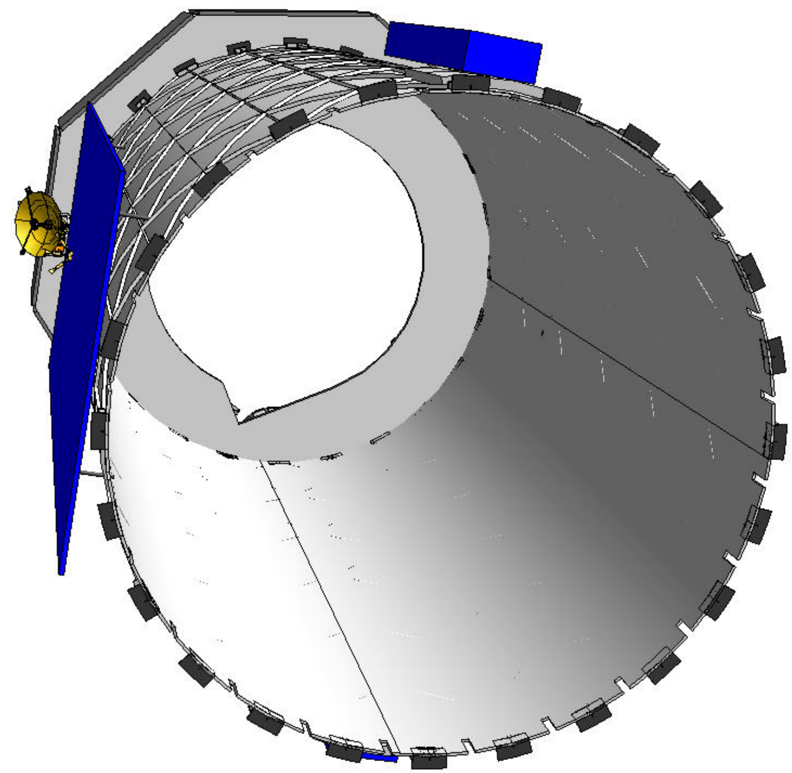
Venting during ascent is assured by 14 venting assemblies embedded in the Fixed Metering Structure

Spacecraft Module

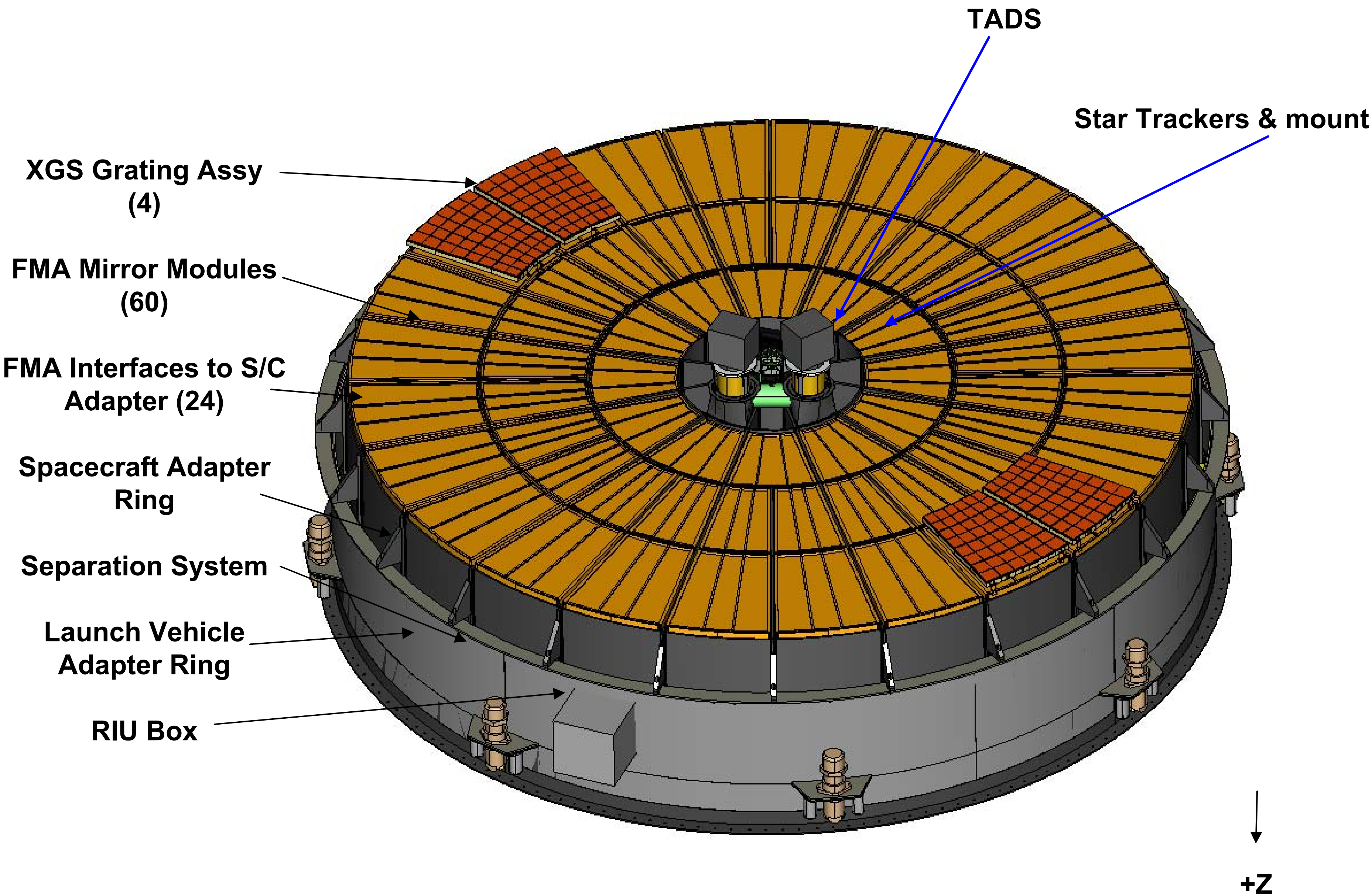


Spacecraft Bus

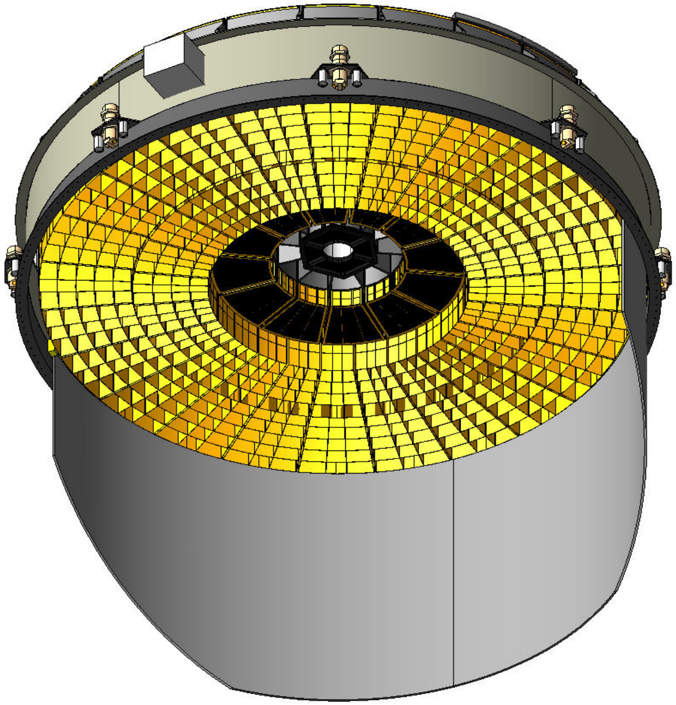
Fixed Metering Structure

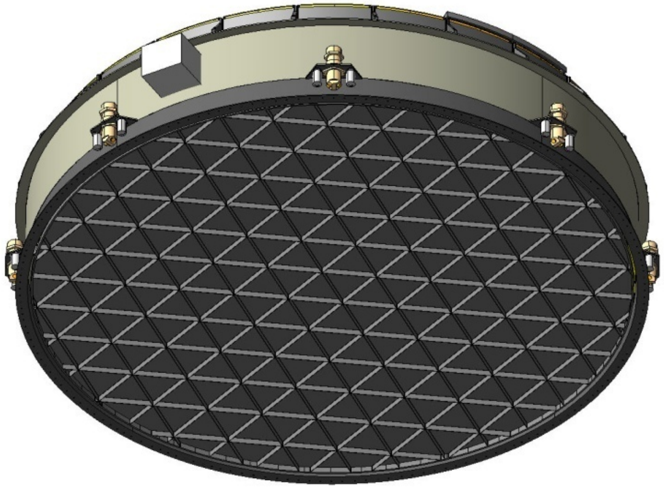


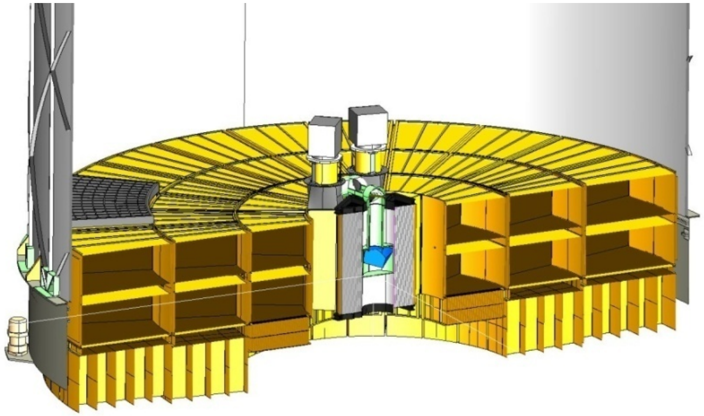
Optics Module Aft End

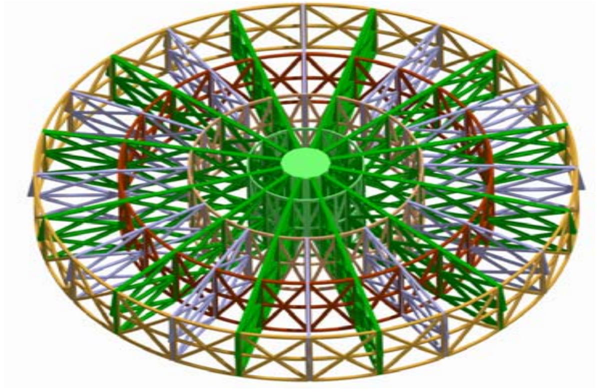


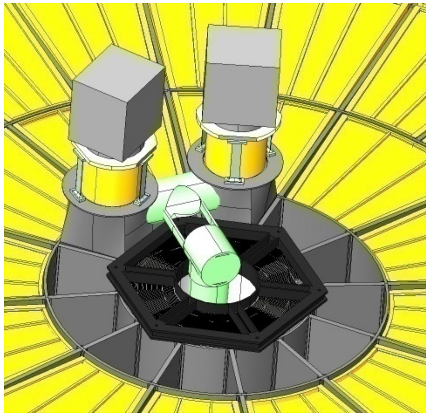
Optics Module







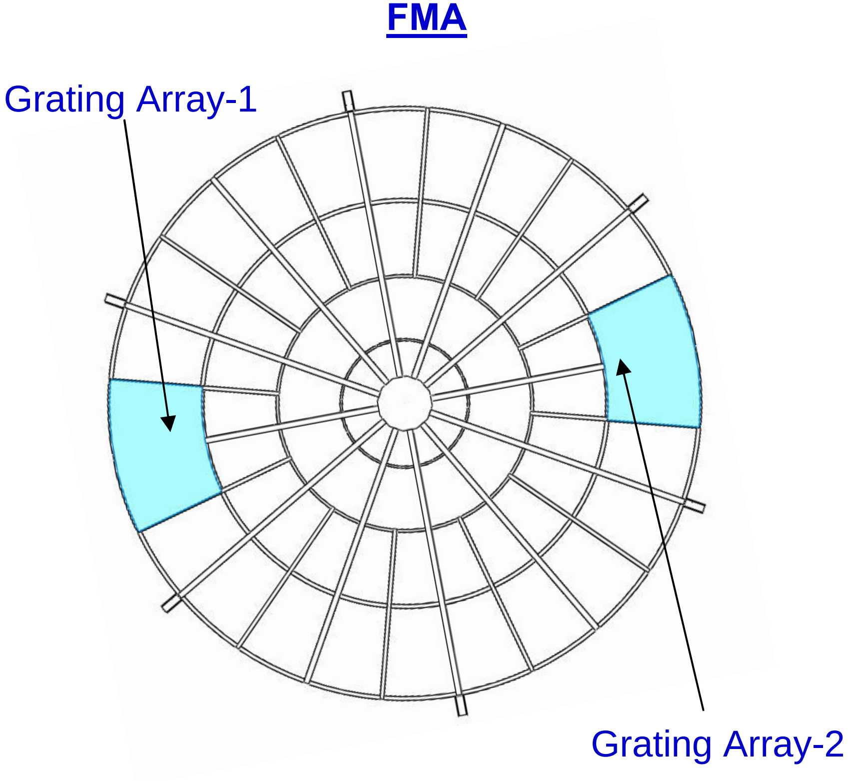




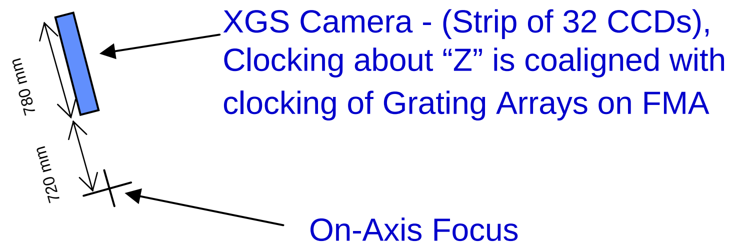
CAT Grating Spectrometer Layout

- Two grating arrays mount on Flight Mirror Assembly. Both arrays project rays to the same CCD readout
- Each grating array covers 30 degrees of the FMA outer annulus
- The FMA outer module mirror consists of nested mirror pairs
- Readout by a 780 m long CCD Camera with a strip of 32 CCD's

FMA

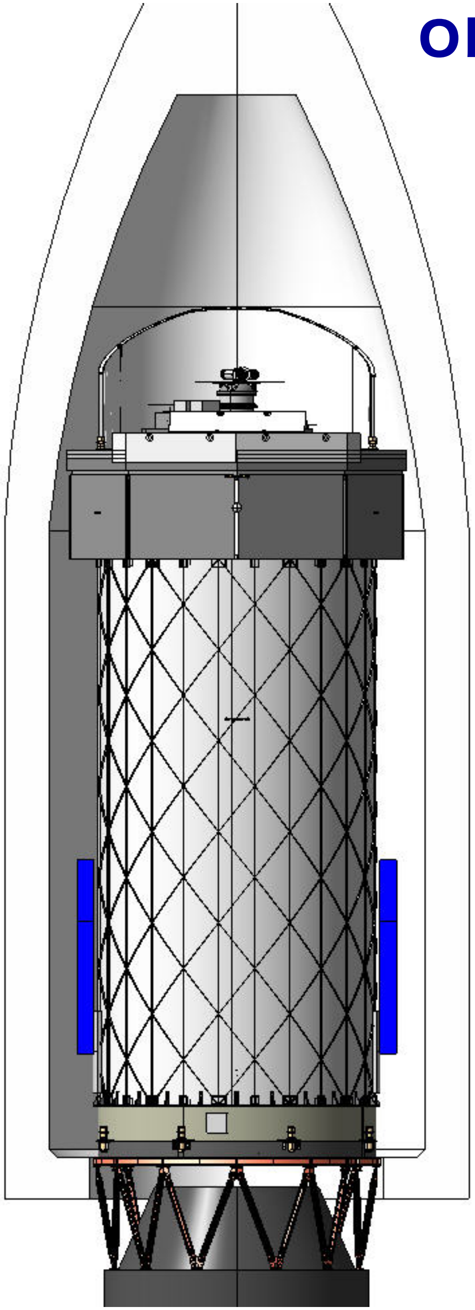


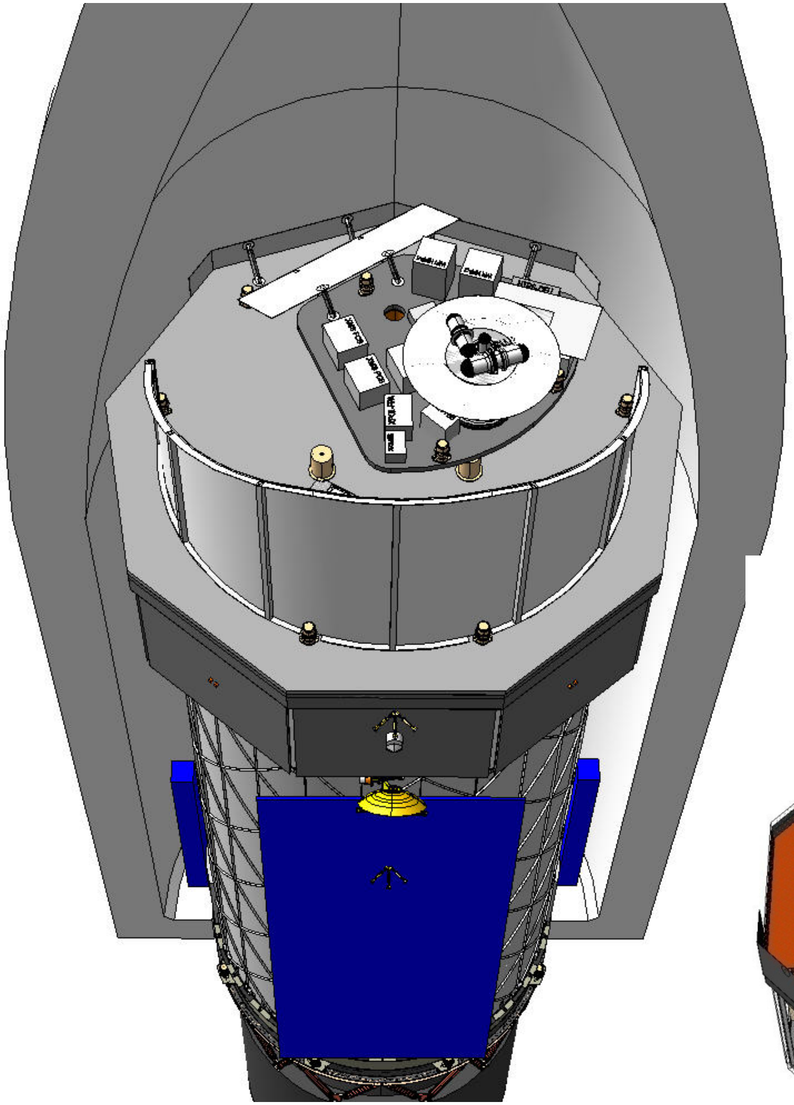
XGS Camera on FIP

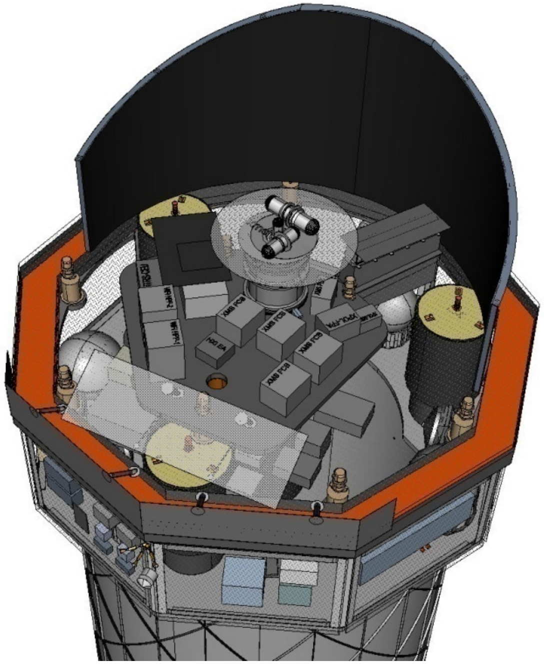


Readout range:
$m\lambda$=25 Å to 77 Å
(0.3 to 1 keV)

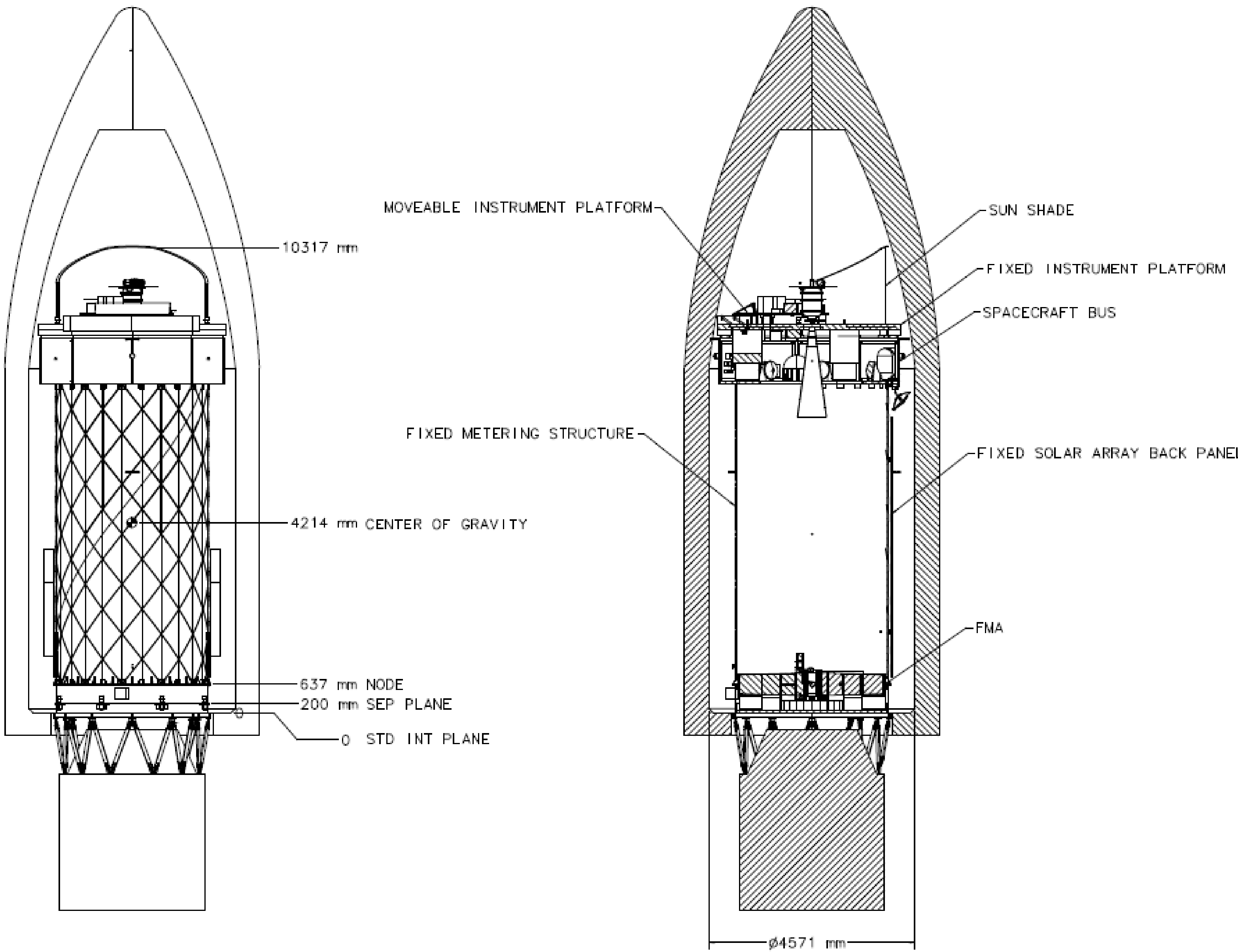
Observatory Launch Configuration





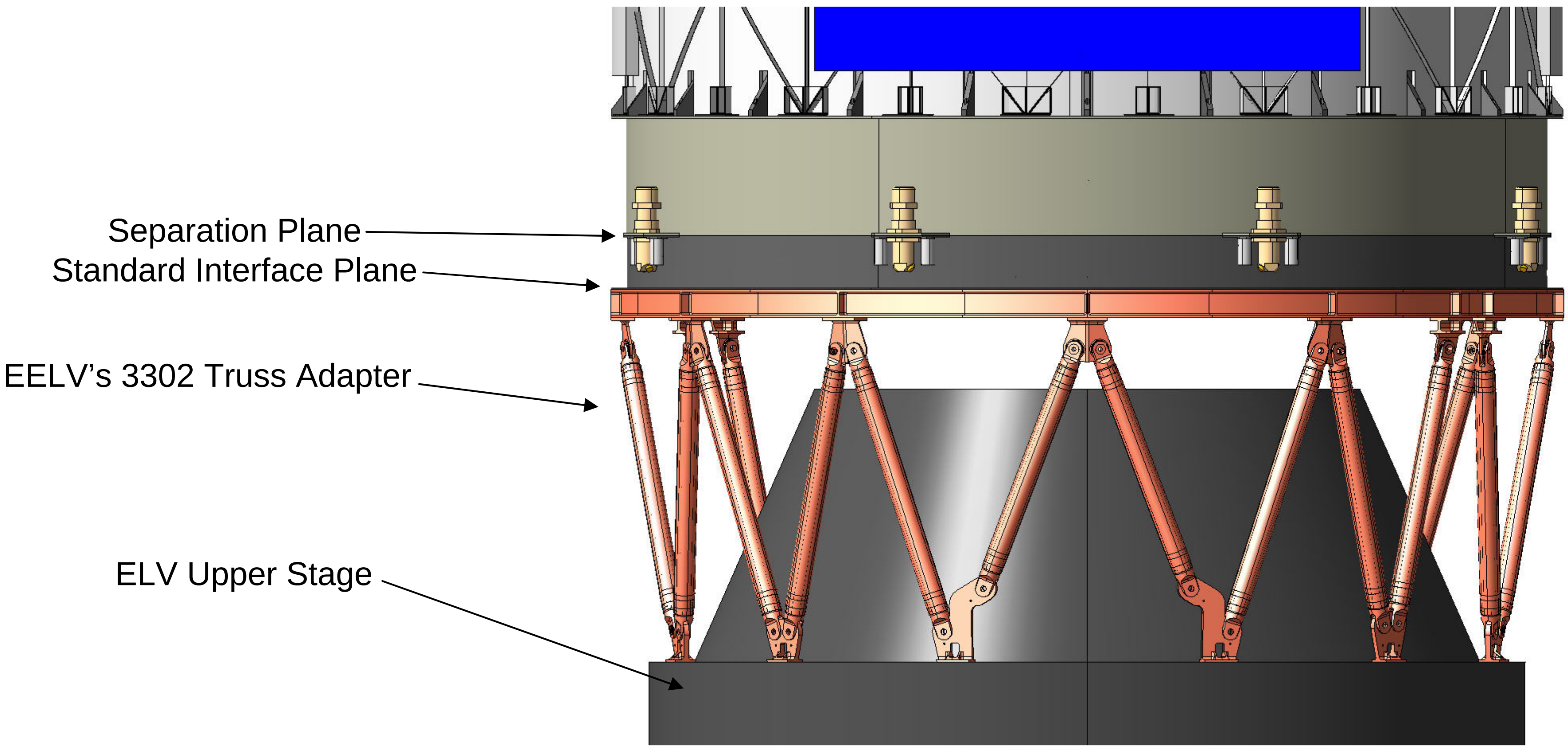


Observatory Launch Configuration



Launch Vehicle Interfaces

- Upper Stage interfaces to an EELV 3302 Truss Adapter
- Launch Vehicle Adapter (LVA) bolts to 3302 Truss Adapter
  - 3.3 m diameter, 1 m tall
- Spacecraft Adapter attached to LVA via sep-nuts
  - Redundant-NSI actuated Sep-nut release system with push-off springs



Launch Configuration - Center of Mass Location

- The 3302 Truss adapter limits the Center of Mass above the Launch Vehicle Standard Interface Plane to < 5.7 m
- IXO's Center of Mass is 4.21 m above the Launch Vehicle Standard Interface Plane

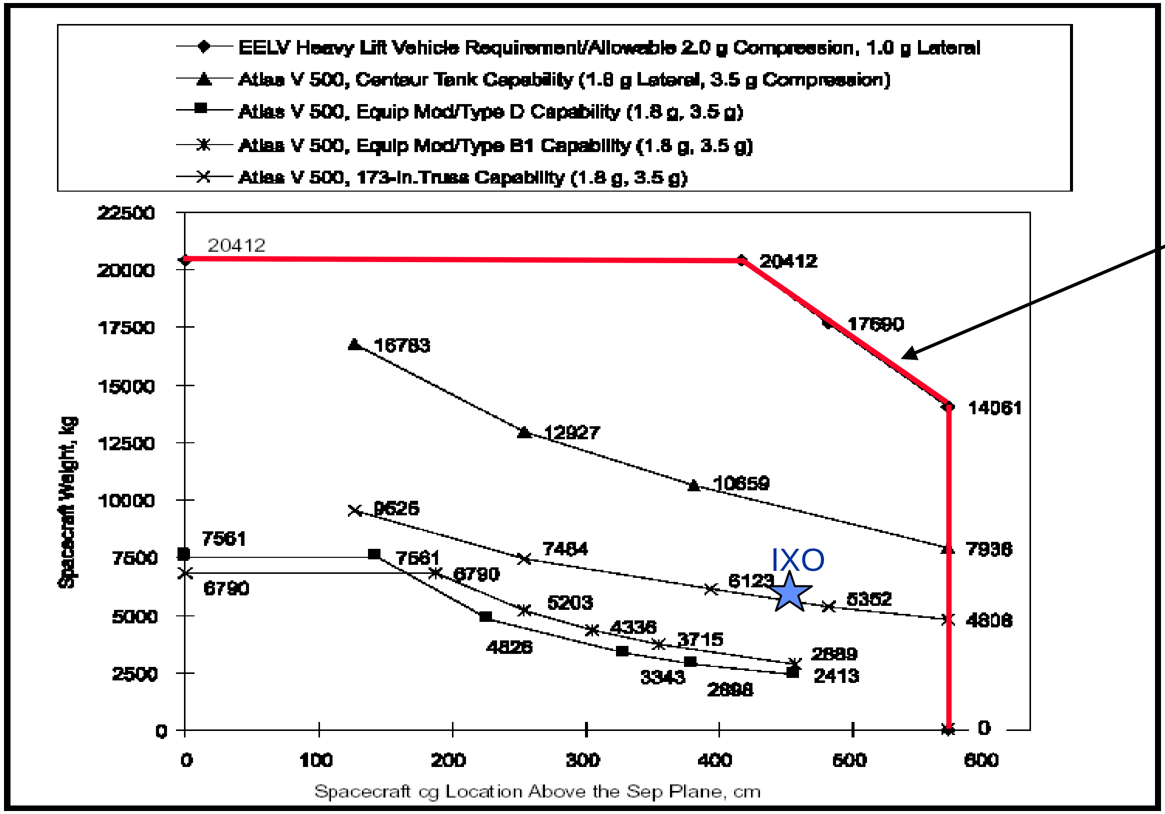


Figure 4.1.2.3-2 Atlas V 500 Allowable cg Location

from the "EELV standard interface specification document" dated September 6, 2000.

Subsystems Overview

Subsystems Overview

- **GN&C**
  - Pointing Requirements (all met):
    - 15 as control, 1 as knowledge, 0.2 as jitter, all (3σ)
  - Solar Pressure Torque @ 1.8m CM/CP offset
    - Pseudo-continuous offload w/ 0.9 N monoprop thruster; ~0.11 s burn every 18 minutes; yields 0.165 arcsec pointing deviation
  - All COTS components
    - 2 ea. AST-301 star trackers: 0.45 as (3σ, after cal), Coarse Sun Sensors, SIRU
    - 5 ea. HR-16 reaction wheels in biased arrangement
    - Distributed Telescope Aspect Determination System: 0.75 as (3σ)
  - Digital Control (PID), 0.02 Hz Bandwidth
- **Propulsion**
  - NTO/Hz Bi-prop pressure regulated main propulsion system and monoprop trim
  - 12 ea. 22 N thrusters
    - 22 N Thrusters can be arranged in forceless couples w/ < 0.5 mm/s per day residual delta-v
  - 4 ea. Aerojet MR-103 0.9 N thrusters
    - Redundant 0.9 N thruster pairs used for real-time solar torque offloading
  - Tanks sized for 10 years+ propellant at max mass
    - 2 ea. Hz tanks: PSI/ATK 80364-1 (MEOP: 400 psia (28 bar))
    - 2 ea. NTO tanks: PSI/ATK 80304-1 (MEOP: 400 psia (28 bar));
    - 1 ea. He: PSI COPV 80412-1 (MEOP: 2,176 psia (150 bar))
- **Mechanical**
  - Modular design supports parallel system I&T at multiple locations
  - Advanced lightweight composites
  - All single failure tolerant mechanisms and deployables
    - LV Separation System, HGA, Ultraflex S/As, Fore Sunshade, Deployable Metering Structure, Jettisonable FMA Outer Cover, Deployable FMA Inner Cover, Moveable Instrument Platform, Focus Mechanisms, Filter Wheel; OP XGS Translation Stage
- **RF Comm**
  - Ka-band
    - Science data and TT&C at 26 Mbps via gimbaled 0.7 m HGA to DSN 34 m
  - S-band
    - TT&C at 8/2 kbps via HGA to DSN 34 m
    - Omni to DSN 34 m
    - Omni to TDRSS for launch and LEO critical events
  - One 30 minute contact / day
    - Continuous DSN contact during first month commissioning, and two 30 min contacts / day during cruise for OD
    - 26 Gbit / day @ low data rate
    - Worst case 212 Gbits (@ peak data rate) << once / month, needs 2 hour additional contact
    - Ranging and doppler during daily contacts, alternating northern and southern hemisphere station contacts
  - Observations continue during downlink

Subsystems Overview

- C&DH
  - Four Avionics boxes plus USO
    - Main C&DH and Integrated Avionics on SM; RIU on IM; RIU on OM
  - BAE RAD 750 SBC (6U)
    - Power PC 750 µprocessor
  - Networked highly redundant Spacewire architecture
  - 3 days + storage
    - 200 Gbit SDRAM board for required 60 hour nominal plus 12 hour peak data rate; have 300 Gbit : 3 for 2 redundancy
- Electrical Power
  - 26 m^2 total Solar Array area
    - Body mounted solar array: 13.5 m^2 3200W CBE (BOL) allows for indefinite safe mode
    - Ultra-flex deployable arrays: 2 ea 6.25 m^2, 12.5 m^2 total area, 3400W CBE (BOL) also contribute to reducing CM-CP offset
  - 6600W CBE (BOL) / 5200W CBE (EOL) Power
  - S/A output routed to PSE for regulated 28VDC
  - 100 AH LiIon battery
    - Sized for Launch mode
  - Electrically independent FMA Temperature Control power system
    - Heater regulated directly on temperature
- Thermal
  - Traditional thermal control (VCHP's, radiators, heaters w/ thermostats, MLI blankets)
  - Shared radiator for Instruments electronics
  - Thermally and electrically independent FMA thermal control system
- Flight Software
  - C&DH/FSW provides:
    - Commands and time distribution
    - ACE and PSE functions (no separate ACE, PSE)
    - Mechanisms control
  - Instrument packages are responsible for any data compression, packetization and time stamping
  - Reuse LRO C&DH FSW
- Micrometeoroid Protection
  - Whipple Shield Shroud (two MLI blankets spaced at 10 cm):
    - 35 penetrating impacts in 10 years
  - Fixed Metering Structure:
    - 1-2 penetrating impacts in 10 years
- Radiation
  - TID for 100-mil Al shield: 27 krad / 10 years (54 krad parts)
  - Severe environment for single events effects
  - Solar Max: 2020 – 2025
- Mission Ops
  - Data Latency:
    - 72 hour required, 24 hour goal
  - Simple ops concept;
    - 8x7 profile for routine ops, auto for unstaffed ops
  - All GOTS/COTS-based
  - Reuse existing MOC

System Resources, Margins, and Associated Issues

Observatory Level Mass Summary

Mirrors	Estimate	Avg. MGA	Max. Exp. Mass
Flight Mirror Assembly	1731	16%	2009
Mirrors Total	**1731**	**16%**	**2009**

Payload	Estimate	Avg. MGA	Max. Exp. Mass
X-ray Microcalorimeter Spectrometer	263	24%	327
WFI/HXI	89	26%	111
X-ray Grating Spectrometer	50	21%	61
XPOL	9	20%	11
HTRS	23	22%	27
Payload Accommodations	134	22%	164
Payload Total	**568**	**24%**	**701**

Subsystems	Estimate	Avg. MGA	Max. Exp. Mass
Avionics	62	22%	75
Communications	30	4%	32
Attitude Control	107	6%	114
Structure and Mechanisms	1108	15%	1269
Power	119	8%	128
Propulsion (dry)	56	3%	57
Thermal	158	19%	189
Harness	273	30%	355
Subsystems Total	**1912**	**16%**	**2219**

Observatory	Estimate	Avg. MGA	Max. Exp. Mass
Science Payload Total	2299	18%	2710
Bus Total	1912	16%	2219
Observatory Dry Mass	**4211**	**17.1%**	**4930**
Propellant Mass (10 yrs)			191
Observatory Wet Mass			**5121**

LV Throw Mass Properties		Max. Exp. Mass
Atlas V 551 Med Fairing Contractual Throw Mass		6425
3302 Truss PAF (stays with LV)		200
Separation System LV Side		90
LV Throw Mass available to lift IXO Wet		**6135**

Mass Margins		Max. Exp. Mass
LV Limited Max IXO Wet Mass [kg]		**6135**
Propellant in LV Limited Max IXO [kg]		229
LV Limited Max IXO Dry Mass [kg]		**5906**
Wet Mass Growth Project Margin (MEV to LV Limit) [kg]		1014
Wey Mass Growth Project Margin (MEV to LV Limit) [%]		19.8%
Total Possible Wet Mass Growth (CBE to LV limit) [kg]		1761
Total Possible Wet Mass Growth (CBE to LV limit) [%]		40.3%

Module Level Mass Summary

Item	CBE [kg]	Composite Mass Growth Allow. [%]	Max Expected Mass [kg]
Instrument Module (IM)	**736**	22.6%	**902**
XMS	263	24.4%	327
CAT XGS IM (Camera+ Detector)	41	18.8%	49
WFI/HXI	89	25.7%	111
XPOL	9	20.1%	11
HTRS	23	21.6%	27
Payload Accommodation IM	46	21.1%	56
GN&C IM	2	47.2%	3
Avionics IM	14	46.6%	21
Mech IM	141	15.7%	163
Harness IM	59	30.0%	76
Therm IM	51	15.1%	58
Deployment Module (DM)	**439**	17.1%	**513**
Mech DM	316	12.2%	355
Harness DM	118	30.0%	154
Therm DM	4	15.0%	5
S/C Module (SCM)	**1084**	14.6%	**1242**
GN&C SCM	80	3.0%	83
Mech SCM	586	15.5%	677
Propulsion Hardware SCM	56	3.0%	57
Therm SCM	86	22.6%	105
Power SCM	119	8.3%	128
Harness SCM	92	30.0%	120
RF Comm SCM	30	4.2%	32
Avionics SCM	35	15.0%	40
Optics Module (OM)	**1952**	16.4%	**2272**
FMA (w/ HXT)	1731	16.1%	2009
CAT XGS OM (Gratings)	9	31.6%	12
Payload Accommodation OM	88	22.4%	108
GN&C OM	24	14.2%	28
Avionics OM	12	15.0%	14
Mech OM	65	15.3%	75
Harness OM	4	30.1%	5
Therm OM	18	17.1%	21
Observatory Dry Mass	**4211**	17.1%	**4930**
Propellant Mass (10 Years, .8Mkm)	163	17.1%	191
Observatory Wet Mass	**4374**	17.1%	**5121**
Launch Vehicle Throw Mass Properties			
Atlas V 551 Med Fairing Contractual Throw Mass			6425
3302 Truss PAF (stays with LV)	194	3%	200
Separation System LV Side	78	15%	90
LV Throw Mass available to lift IXO Wet			**6135**
Mass Margins			
LV Limited Max IXO Wet Mass [kg]			6135
Propellant in LV Limited Max IXO [kg]			229
LV Limited Max IXO Dry Mass [kg]			5906
Wet Mass Growth Project Margin (MEV to LV Limit) [kg]			**1014**
Wet Mass Growth Project Margin (MEV to LV Limit) [%]			**19.8%**
Total Possible Wet Mass Growth (CBE to LV limit) [kg]			**1761**
Total Possible Wet Mass Growth (CBE to LV limit) [%]			**40.3%**

Mission Delta-V, Propellant, and Margins Analysis

DELTA V BUDGET FOR 10 YEARS				
	Estimate	ACS Tax	Contingency	Subtotal
Launch Window	10 m/sec	5%	0%	11 m/sec
ELV Dispersion Correction	20 m/sec	5%	0%	21 m/sec
Mid-Course Correction	10 m/sec	5%	5%	11 m/sec
Orbit Lowering Maneuver	0 m/sec	5%	0%	0 m/sec
L2 Stationkeeping for 10 years	40 m/sec	5%	5%	44 m/sec
Momentum Management for 10 years	9.8 m/sec	0%	5%	10 m/sec
De-orbit	1 m/sec	5%	5%	1 m/sec
Total Equivalent Delta V [m/s]				98.0

ALLOCATION PROPELLANT BUDGET	
	Allocation
Allocation Dry Mass	4929.9 kg
Prop Mass (use equivalent Isp =275)	182.1 kg
5% Ullage and Residual	9.1 kg
Allocated Propellant Mass	191.2 kg

Margin Analysis w/ Allocated Wet Launch Mass of:	5121 kg	
Tanks max load Propellant mass	281.0 kg	
Tanks max load Propellant mass margin	47.0%	rel. to Propellant required for nominal Delta-v
Tanks max load Delta-v [m/s]	142.7	
Tanks max load Delta-v margin	45.6%	rel. to nominal Delta-v

Margin Analysis w/ max LV Throw Mass of:	6425 kg	
Tanks max load Propellant mass	281.0 kg	
Tanks max load Propellant mass margin	12.8%	rel. to Propellant required for nominal Delta-v
Tanks max load Delta-v [m/s]	115.1	
Tanks max load Delta-v margin	17.4%	rel. to nominal Delta-v

Observatory Level Power Loads

Max. Exp. Value (CBE + 30%)	Launch	Cruise	Science	Downlink	Slew	Safehold	Max
Observatory	**508**	**3620**	**3648**	**3681**	**2338**	**3102**	**4777**
S/C	144	1169	1197	1229	1571	1836	2016
Payload	364	2452	2452	2452	2452	1265	2762

S/C *Max. Exp. Values (CBE +30%)*

	Launch	Cruise	Science	Downlink	Slew	Safehold	Max
S/C Total	**144**	**1169**	**1197**	**1229**	**1571**	**1836**	**2016**
ACS	16	65	70	70	433	57	569
C&DH	98	192	192	203	205	185	229
RF Comm	26	57	57	104	57	57	117
Mech	0	2.4	2.4	2.4	2.4	2.4	2.4
Propulsion	0	7	7	7	13	7	7
Power	5	185	217	219	210	175	305
Harness	0	23	27	27	26	22	38
Thermal	0	637	624	598	624	1332	749

Payload *Max. Exp. Values (CBE +30%)*

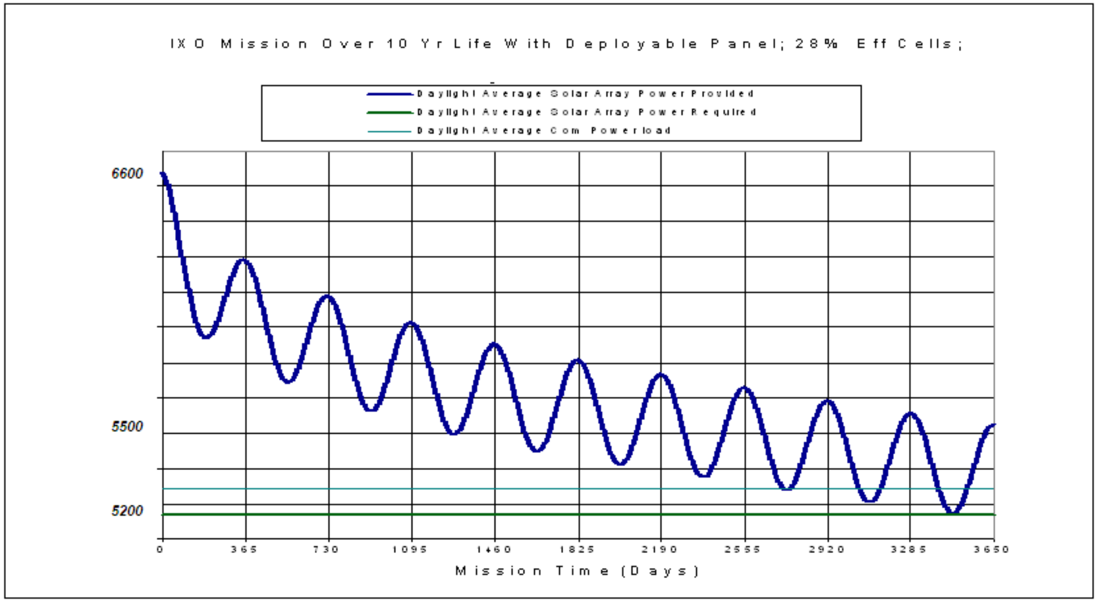
	Mode 1	Mode 2	Mode 3	Mode 3	Max
Payload Total	**2452**	**2338**	**2087**	**2156**	**2762**
FMA	1456	1456	1456	1456	1456
XMS	844	420	420	420	844
WFI	33	289	33	33	289
HXI	6	60	6	7	60
XGS	100	100	100	100	100
XPOL	0	0	60	0	0
HTRS	13	13	13	141	13

Unit Powers *Max. Exp. Values (CBE +30%)*

	Ave	Standby	Safehold	Launch	Peak
Total	**2950**	**1924**	**1265**	**364**	
FMA	1456	1456	1265	364	1456
XMS	844	420	0	0	914
WFI	289	33	0	0	340
HXI	60	6	0	0	60
XGS	100	0	0	0	107
XPOL	60	0	0	0	60
HTRS	141	10	0	0	141

Observatory Level Power Margin

- Observatory Power Loads
  - **Science Mode Max: 3648 W MEV**
  - **Abs Max Power Load: 4777 W MEV**
- Power System Max Output (BOL): 6600 W CBE
  - **81% margin on top of 30% contingency over Science Mode Max load at BOL**
  - **38% margin on top of 30% contingency over Abs Max load at BOL**
- Power System Absolute Minimum Output (EOL, 10 yrs): 5200 W CBE
  - **43% margin on top of 30% contingency over Science Mode Max load at EOL**
  - **8.9% margin on top of 30% contingency over Abs Max load at EOL**
- Power is not a problem for IXO at L2
  - **IXO is actually <u>depopulating (!)</u> solar cells from the 3.4 m dia Ultraflex arrays, flown to balance solar pressure**
  - **If needed, more solar cells can be added to the existing Ultraflex panels at < 0.5 kg / 100W**



Observatory Level Injection and Safe Mode Power

- Payload is unpowered at launch. Spacecraft in Launch Survival mode w/ min. power loads
  - FMA warmed to safe high survival temp till T-0, then slowly cools down during orbit insertion and Launch Vehicle Separation
  - When the FMA temperature reaches the survival cold limit, the FMA Survival Heaters come on
  - LV separation at L + 30 min to L + 125 min
- Launch Configuration Observatory Power is 508W MEV (incl. FMA survival heat w/ Covers on)
  - The 2800 Wh (100 Ah) LiIon battery (at 70% DoD) provides for Observatory survival till past L+ 5 hrs even w/o sun
  - With the body mounted solar arrays sun pointed (before or after LV separation) the Observatory can maintain Safehold indefinitely, even w/o the Ultraflex S/A panels deployed
- Deployed in-orbit survival power is 3102 W MEV (incl. FMA survival heat w/ Covers off)
  - IXO is sun pointed in full 100% sun during the entire mission
  - Loss of power positive sun pointing attitude at any time for any duration is an unacceptable failure mode not envisioned
  - Nevertheless, even in such an event, the battery allows for over an hour of full Observatory safehold w/o any solar energy input

Max. Exp. Value (CBE + 30%)	Launch	Safehold	Max
Observatory	508	3102	4777
S/C	144	1836	2016
Payload	364	1265	2762

S/C *Max. Exp. Values (CBE +30%)*

	Launch	Safehold	Max
S/C Total	144	1836	2016
ACS	16	57	569
C&DH	98	185	229
RF Comm	26	57	117
Mech	0	2.4	2.4
Propulsion	0	7	7
Power	5	175	305
Harness	0	22	38
Thermal	0	1332	749

Instrument Data Requirements

- **Storage Size Requirement**

    48 hours including 12 hours of peak rate and 36 hours of average rate (this is called 48-hour-peak-volume)

    +

    up to 1 day of missed passes (i.e., an additional 24 hrs of avg data rate)

= A TOTAL of 12 hours peak plus 60 hours of avg data

(Assumed 100% efficiency for this 72 hour storage sizing)

- **Downlink / Latency Requirement**
  - **Data collected at average rate must meet 72 hour latency requirement**
  - **Size to downlink 48-hour-peak-volume over period of 2 weeks above the avg. rate required for data latency of 72 hours**
  - **Allows for 2 bright source observations (peak) per month**

- **5 year Mission Data Composition Requirement**
  - **97% of the time data collected at low data rate**
  - **3% of the time data collected at peak data rate**

Observatory Level Data Generation and Storage Summary

Element		CBE Data Rates (kbps) (w/o contingency)		
		Average	Peak	Comments
FMA	Science	0.0		
	Housekeeping	1.0	1.0	
	Total FMA	**1.0**	**1.0**	
XMS	Science	25.6	1,680.0	
	Housekeeping	4.0	4.0	
	Total XMS	**29.6**	**1,684.0**	
WFI	Science	45.0	1,000.0	4.5 Mbps for high
	Housekeeping	0.2	0.2	
	Total WFI	**45.2**	**1,000.2**	
HXI	Science	10.0	1,000.0	based on BEPAC HXT
	Housekeeping	0.8	0.8	
	Total HXI	**10.8**	**1,000.8**	
XGS	Science	128.0	1,280.0	
	Housekeeping	1.0	1.0	
	Total XGS	**129.0**	**1,281.0**	
X-POL	Science	300.0	1,000.0	
	Housekeeping	0.2	0.2	
	Total X-POL	**300.2**	**1,000.2**	
HTRS	Science	50.0	50.0	
	Housekeeping	0.2	0.2	
	Total HTRS	**50.2**	**50.2**	
Total by Mode	**Mode 1**	**159.6**	**2,966.0**	
	Mode 2	**186.0**	**3,283.0**	
	Mode 3	**430.2**	**2,282.2**	
	Mode 4	**180.2**	**1,332.2**	
	Weighted "daily average"	**199.3**	**<<< Size System to this**	

STORAGE MODE 1 (Estimate w/o contingency)	Rate	Unit
Low Science Data Rate per sec	159.6	kbps
Low Science Data Rate - Data Volume per hour	0.6	Gbit
Low Science Data Rate - Data Volume per day	13.8	Gbit
Low Science Data Rate - Data Volume per 60 hours	34.5	Gbit
High Science Data Rate per sec	2,966.0	kbps
High Science Data Rate - Data Volume per hour	10.7	Gbit
High Science Data Rate - Data Volume per 12 hours	128.1	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Mode 1 Storage Total	**163.0**	**Gbit**

STORAGE MODE 2 (Estimate w/o contingency)	Rate	Unit
Low Science Data Rate per sec	186.0	kbps
Low Science Data Rate - Data Volume per hour	669.6	Gbit
Low Science Data Rate - Data Volume per day	16.1	Gbit
Low Science Data Rate - Data Volume per 60 hours	40.2	Gbit
High Science Data Rate per sec	3,283.0	kbps
High Science Data Rate - Data Volume per hour	11.8	Gbit
High Science Data rate 12 hours	141.8	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Mode 2 Total	**182.3**	**Gbit**

STORAGE MODE 3 (Estimatew/o contingency)	Rate	Unit
Low Science Data Rate per sec	430.2	kbps
Low Science Data Rate - Data Volume per hour	1,548.7	Gbit
Low Science Data Rate - Data Volume per day	37.2	Gbit
Low Science Data Rate - Data Volume per 60 hours	92.9	Gbit
High Science Data Rate per sec	2,282.2	kbps
High Science Data Rate - Data Volume per hour	8.2	Gbit
High Science Data rate 12 hours	98.6	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Mode 3 Total	**191.9**	**Gbit**

STORAGE MODE 4 (Estimatew/o contingency)	Rate	Unit
Low Science Data Rate per sec	180.2	kbps
Low Science Data Rate - Data Volume per hour	648.7	Gbit
Low Science Data Rate - Data Volume per day	15.6	Gbit
Low Science Data Rate - Data Volume per 60 hours	38.9	Gbit
High Science Data Rate per sec	1,332.2	kbps
High Science Data Rate - Data Volume per hour	4.8	Gbit
High Science Data rate 12 hours	57.6	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Mode 4 Total	**96.8**	**Gbit**

Observatory Level Data Storage Margin

- **Observatory Data Storage volume: 300 Gbits**
- **Observatory max nominal 60 hr data volume ("Low Data Rate Mode" for 60 hrs) : 92 Gbits (CBE)**
  - **300% margin (on CBE)**
- **Observatory abs max 60 hr data volume ("Hi Data Rate Mode" for 12 hours plus "Low Data Rate Mode" for 48 hours) : 192 Gbits (CBE)**
  - **50% margin on abs max (CBE)**

Observatory Level Downlink Summary

Downlink	Rate	Unit
"Low Science Data Rate" - Data Volume per day	17.2	Gbit
Instr. Hskp (incl. in Sci. Data Rate)	0.0	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Contingency 30%	5.3	Gbit
Reed Solomon Overhead 15%	3.4	Gbit
Total Downlinked "Low Science Data Rate" Volume per day	**26.3**	**Gbit**
Actual downlink rate to DSN 34 m w/ 70 cm HGA	26.0	Mbps
Actual "Regular" Downlink Time	**16.8**	**min**

Downlink	Rate	Unit
"High Science Data Rate" - Data Volume per 12 hours	141.8	Gbit
Instr. Hskp (incl. in Sci. Data Rate	0.0	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Contingency 30%	42.5	Gbit
Reed Solomon Overhead 15%	27.7	Gbit
Total Downlinked "High Science Data Rate" Volume on "worst" day	**212.4**	**Gbit**
Actual downlink rate to DSN 34 m w/ 70 cm HGA	26.0	Mbps
Actual "Regular" Downlink Time	*136.2*	*min*

Observatory Level Downlink Volume Margin

- **Nominal daily downlink volume** (w/ nominal 30 minutes DSN contact at 26 Mbps)**: 50 Gbits / day**

- **Observatory max nominal downlink volume per 24 hours** ("Low Data Rate Mode" for 24 hours) **: 26 Gbits / day** (Max Expected Value, incl. 30% MGA)
  - ~100% margin (on top of 30% contingency)

- **Observatory abs max downlink volume per 24 hours** ("Hi Data Rate Mode" for 12 hours plus "Low Data Rate Mode" data volume for 12 hours) **: 212 Gbits** (Max Expected Value, incl. 30% MGA)
  - Downlink by either: increasing DSN contact time to ~2 hours once a month during the "Hi Data Rate Mode" period
    - Feasible, pay DSN per minute w/ 30 minutes min. charge
  - Or: store extra data volume (have storage space) and "drain away" extra data over several subsequent daily 30 min DSN contacts

Timing Budget

Timing Contributors	Accuracy	Unit	Comments
DSN Clock Accuracy	12	microsec	Uses atomic clock
Uplink Delay Offset Accuracy	1	microsec	Uplink transmission delay is subtracted out with offset determined by analysis and test. This is the accuracy of that
Spacecraft Clock Accuracy	38	microsec	Ultra stable oscillator (stable to 1.59 microsec / hour) with a once per day ground uplink time correlation
C&DH to Instrument 1 Hz timing signal accuracy	1	microsec	1 Hz signal is synchronized to ultra stable oscillator clock
Instrument clock accuracy over 1 second	20	microsec	Drift of crystal oscillator over 1 second
RSS Total	45	microsec	Leaves 28 us for Orbit Detemination accuracy

Speed of Light	0.3	km/microsec
Orbit Determination requirement	17	km

Orbit Determination, IXO vs. JWST

- JWST's navigation / stationkeeping /momentum unloading scenario
  - JWST has navigation requirements of 50 km in position and 2 cm/s (3?, RSS) in velocity (to support stationkeeping maneuver planning)
  - JWST plans on receiving 30 minutes of DSN S-band tracking data each day using Canberra, Goldstone, & Madrid
  - DSN tracking contacts will be alternated such that there is a maximum of 72 hours between successive northern (Goldstone & Madrid) and successive southern (Canberra) passes
  - JWST stationkeeping maneuvers will occur every 22 days (for this study they ranged in size from 2 cm/s to 8 cm/s)
  - JWST expects eight momentum unloads between every stationkeeping maneuver (ranged in size from 0.4 cm/s to 0.9 cm/s)
  - JWST momentum unloads should have a minimum of 50 hours between each unload
  - JWST will have no momentum unloads during the day before the stationkeeping maneuver
  - This scenario has forced JWST to go to a sequential filter orbit determination process using a Kalman filter.
- Given those results, JWST is getting better than 10 km position accuracy (after convergence of the filter) and are better than 1 cm/s velocity accuracy to plan their stationkeeping maneuvers.
  - These numbers do become degraded somewhat in the event of missed passes or the loss of Southern or Northern passes.

- IXO's solar disturbance reduction plan appears feasible
  - 16 micro-meter/sec pulses every 18 minutes
- Sequential filter will converge on the navigation solution
  - Confirmation by detailed analysis is required
- IXO will likely meet a better than 10 km position accuracy
  - Consistent with timing requirement

CPU / Flight Software Margins

Resource	Amount Available	Current Estimate	Current Margin	GOLD Rule Required Margin @Phase A
CPU (BAE750)	100%	29.10%	71%	50%
uP RAM(kB)	32768	6471	80%	50%

For this chart, Margin = (Available – Estimate) / Available

Observatory Level Pointing Margins

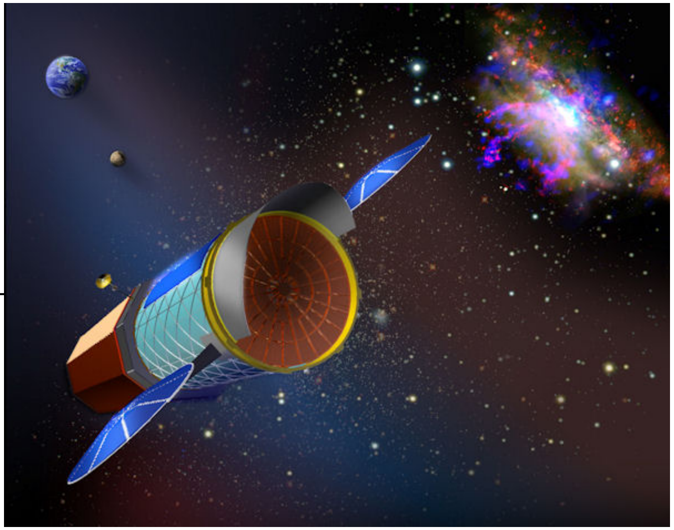
Term	Requirement	Predicted Performance	Margin
• Image Position Reconstruction Knowledge	• Radial: 1 arcsec (3σ) • (that is pitch and yaw combined, equivalent to ~0.7" pitch and ~0.7" yaw)	• Radial: .88 arcsec (3σ)	14%
• Image Position Control	• Pitch and Yaw: 12 arcsec (3σ)	• On-Axis Inst's: 1.13 arcsec (3σ) • XGS: 7.5 arcsec (3σ)	1060% 60%
• Jitter • (excluded from the Image Position Knowledge requirements)	• 200 milliarcsec (3σ) • over 200 msec	• 20 milliarcsec (3σ) • abs. worst case over any period msec • By Reaction Wheel momentum management in a 5 RW configuration, a steady state jitter of .2 milliarcsec is achievable	>900%

Slew Margin

- Requirement
  - Complete a 60 degree (yaw) slew in 60 minutes (stop of Observation - to - start of next Observation)
- Slew Performance
  - 60 deg yaw completed in 0.52 hrs (92% margin)
  - 20 deg pitch completed in 0.41 hrs (144% margin)

IXO Systems Definition Document
Chapter 2

Systems Engineering



Definitions,
Systems Engineering Process

Key Terms

Key Terms Defined:

Spacecraft = Observatory minus Science Payload

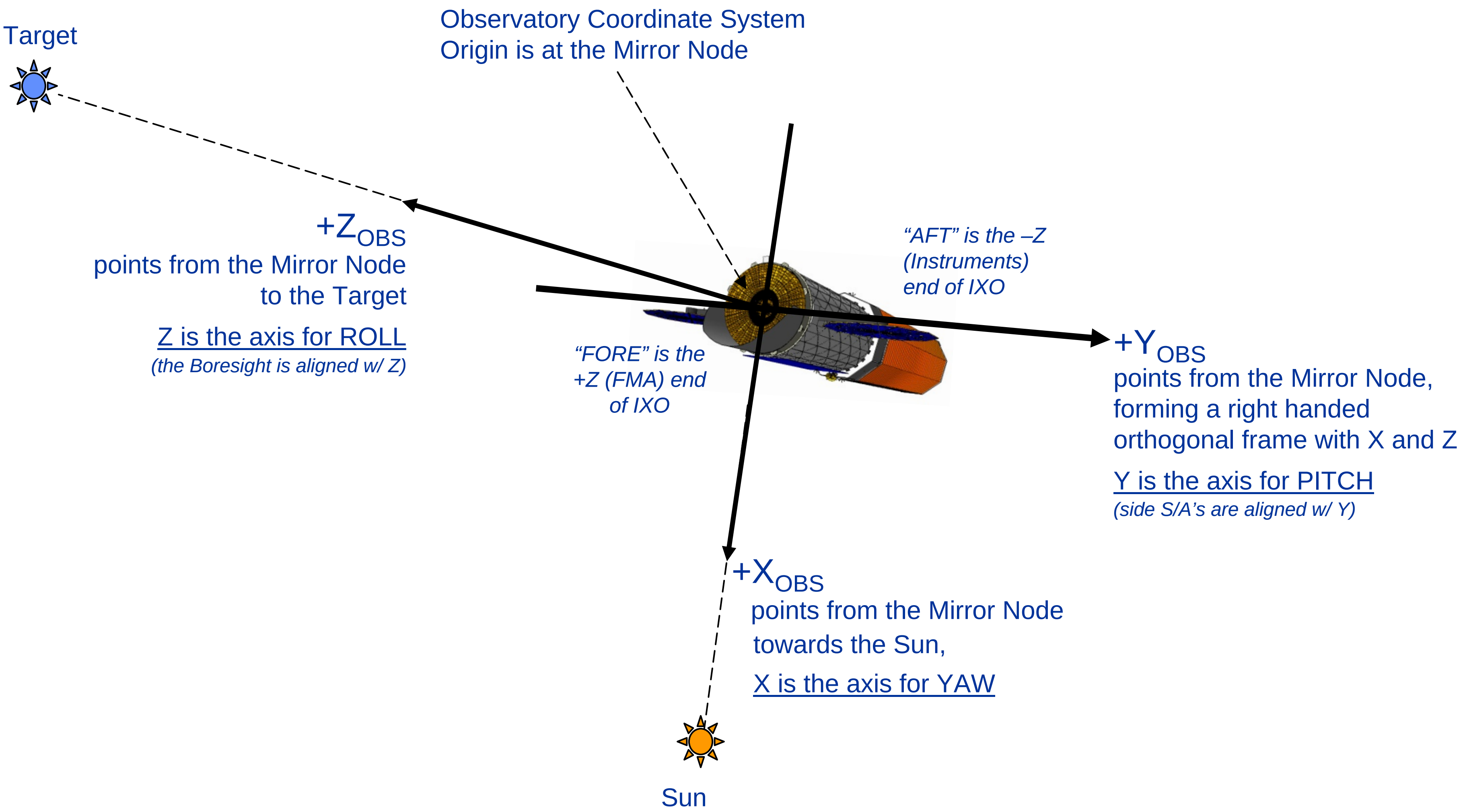
Science Payload = FMA and Instruments

CBE = Current Best Estimate

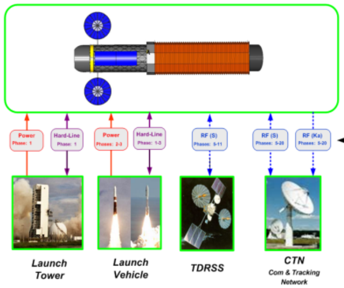
MGA = Maximum Growth Allowance

MEV = Maximum Expected Value = CBE plus MGA

Observatory Coordinate System and Key Terms



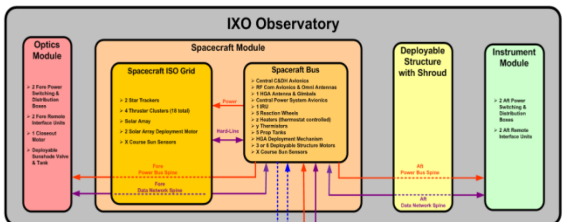
Systematic System Architecture Concept Development; Architectural Level Definitions



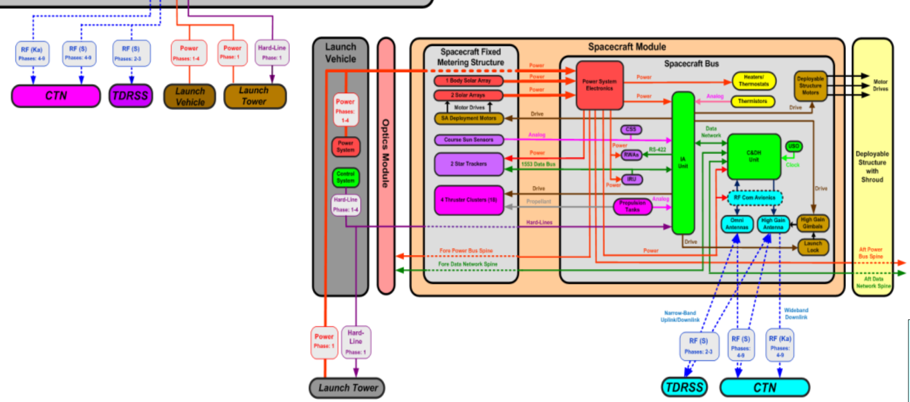
#	Mission Phase
1	Pre-Launch
2	Launch at T0
3	Transfer Trajectory Insertion (TTI)
4	LV Separation:
5	Deploy Solar Arrays & High Gain Antenna
6	Spacecraft full power on
7	Deploy Metering Structure
8	Commence Observatory Checkout
9	ELV Dispersion Corrections
10	Commence Instrument Aliveness Checks
11	Instrument internal background measurement
12	First Mid-Course Correction
13	After outgassing: Jettison / Open Flight Mirror Assembly Covers, turn Cryo on
14	Open Instrument Covers and Gate Valves
15	Calibrate w/ Celestial Targets
16	After Calibration is complete, may start nominal Science Ops, even while in Cruise
17	Second Mid-Course Correction
18	L2 Orbit Insertion (L2OI) w/ Y-Amplitude Lowering Maneuvers
19	At L2, continue with Science Ops
20	EOM Disposal

Observatory Interfaces are present during the mission phases that are annotated by phase # inside the bubbles

Level-1: Mission / Observatory



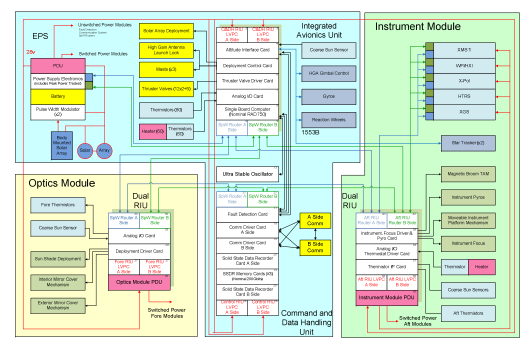
Level-2: Module Functions



Level-3: Subsystems

Present IXO development effort conducted mostly at Level 4

Level-4: Sub-Assemblies



Multilevel Integrated Modeling

IXO's design, and the associated validation and verification, was gradually evolved over four levels of modeling:

- The First Level of Observatory modeling used highly cross-linked Systems Spreadsheets
  - Principal design tool for quick response decisions
  - Dozens of WorkSheets, MEL (organized per WBS breakdown with Module level then spacial sub-ordering)
  - Recursive cross-links to various mass reports; feed and get fed from: propellant, CG, CP, and momentum calculators, etc.
- The Second Level of Observatory modeling used 3D Mechanical design (IDEAS) and 3D PDF models
  - Some models / mockups actually physically built (folded Deployable Shroud)
  - Animations and full videos
- Third Level of Observatory modeling: Advanced Numeric Performance Models
  - 3D Thermal Model
  - FEM and Jitter simulations
  - Control System model and simulations
- Fourth Level of Observatory modeling: Integrated Models
  - Various integrations for various analyses of the Thermal/FEM/ Control System Models

Controlling Systems Engineering Documents

- Process for the Systems Engineering of Goddard Space Flight Center (GSFC) Missions
  - GPR-7120.5A
- NASA Systems Engineering Handbook
  - NASA-SP-2007-6105-Rev-1-Final-31Dec2007
- Mass Properties Control for Space Systems
  - AIAA_S-120-2006_MassPropertiesControl
- Goddard Space Flight Center GOLD Rules
  - GSFC-STD-1000D
- Risk Classification for NASA Payloads
  - NPR_8705_0004+
- Space Mission Analysis and Design
  - Wertz / Larson, Third Edition, 1999

Observatory Level Mass Margin Allocation Process

- **Mass estimation process per AIAA S-120**
  - **Variable "Max Growth Allowance [MGA]" contingency %'s assigned to each MEL line item**
  - **MGA %'s are specified in the Standard as a function of 1.) maturity, and 2.) equipment type (i.e. battery, electronics, structure, etc.)**

Table 1 — Mass Growth Allowance and Depletion Schedule

Major Category	Maturity Code	Design Maturity (Basis for Mass Determination)	Mass Growth Allowance (%)												
			Electrical/Electronic Components 0-5 kg	Electrical/Electronic Components 5-15 kg	Electrical/Electronic Components >15 kg	Structure	Brackets, Clips, Hardware	Battery	Solar Array	Thermal Control	Mechanisms	Propulsion	Wire Harness	Instrumentation	ECLSS, Crew Systems
E	1	**Estimated** 1) an approximation based on rough sketches, parametric analysis, or undefined requirements, 2) a guess based on experience, 3) a value with unknown basis or pedigree.	30	25	20	25	30	25	30	25	25	25	55	55	23
E	2	**Layout** 1) a calculation or approximation based on conceptual designs (equivalent to layout drawings), 2) major modifications to existing hardware	25	20	15	15	20	15	20	20	15	15	30	30	15
C	3	**Preliminary Design** 1) calculations based on a new design after initial sizing but prior to final structural or thermal analysis, 2) minor modification of existing hardware	20	15	10	10	15	10	10	15	10	10	25	25	10
C	4	**Released Design** 1) calculations based on a design after final signoff and release for procurement or production, 2) very minor modification of existing hardware, 3) catalog value	10	5	5	5	6	5	5	5	5	5	10	10	6
A	5	**Existing Hardware** 1) actual mass from another program, assuming that hardware will satisfy the requirements of the current program with no changes, 2) values based on measured masses of qualification hardware	3	3	3	3	3	3	3	2	3	3	5	5	4
A	6	**Actual Mass** measured hardware	No mass growth allowance – use appropriate measurement uncertainty values												
A	7	**Customer Furnished Equipment or Specification Value**	Typically a "not-to-exceed" value is provided; however, contractor has the option to include MGA if justified												

Requirements, Flowdown, Key Drivers

Payload Performance Objectives Flown Down to Payload Complement

Mirror Effective Area	3 m^2 @1.25 keV 0.65 m^2 @ 6 keV 150 cm^2 @ 30 keV 1000 cm^2 (0.3 – 1 keV)
Spectral Resolution (FWHM), over FOV, over band	Δ E = 2.5 eV, 2x2', (0.3 - 7 keV) Δ E = 10 eV, 5x5', (0.3 - 7 keV) Δ E =150 eV, 18', (0.1 - 15 keV) E/ Δ E = 3000, (0.3 - 1 keV) Δ E = 1 keV, 8x8', (10 – 40 keV)
Angular Resolution	$\leq$5 arc sec HPD (0.1 – 7 keV) 30 arc sec HPD (7 - 40 keV)
Count Rate	1 Crab with >90% throughput. Δ E < 150 eV @ 6 keV (0.1 – 15 keV)
Polarimetry	1% MDP on 1 mCrab,100 ksec, 3 σ , 2 - 6 keV
Astrometry	1 arcsec at 3 σ confidence
Absolute Timing	50 μ sec

FMA

- SXT
- HXMM

Five Instruments

- XMS
- WFI/HXI
- HTRS
- X-Pol
- XGS

Example of Payload & Observation Requirements Flown Down to Mission Systems Requirements: XMS Instrument Image Quality Error Budget Flown Down to Pointing Requirements

		Micro-calorimeter Spatial Resolution Goals Error Budget - Mission(1 SXT, single Atlas V Launch)										
		ITEM (HPD - arcsec)	RQMT	Margin		Allocation						RATIONALE
	1	Calorimeter Resolution	5.00	0.62								1 SXT
	2	On-Orbit Single Telescope			4.96							RSS
	3	Calorimeter pixelization error				0.96						3 arc-second pixels, with sub-pixel resolution
	4	Telescope level effects				1.51						RSS
	5	Image Reconstruction errors (over obs)					1.41					RSS
1	6	Attitude knowledge drift						1.00				Chandra experience
	7	FMA/XMS focal plane drift (thermal)						1.00				Chandra experience - includes FID light system
2	8	FMA/XMS vibration effects					0.20					Chandra experience (jitter)
3	9	FMA/XMS misalignment (off-axis error)					0.05					field dependent aberration =+/- 30 arc-sec alignment
4	10	FMA/XMS Focus Error					0.50					Allocation - includes focal plane focus adjustment
	11	FMA On-orbit performance				4.63						RSS
	12	SXT Mirror launch shifts					0.50					Eng est based on Chandra
	13	On-orbit Thermally Driven Errors					1.41					RSS
	14	Bulk temperature effects						1.00				Engineering judgement for +/- 1 C
	15	Gradient effects						1.00				Engineering judgement for 1C gradient
	16	Material Stability					1.00					Est based on Chandra work
	17	FMA/Telescope mounting strain					1.00					Eng estimate based on Chandra experience
	18	FMA, As built					4.14					RSS
	19	Gravity Release						1.00				FEA Analysis using vertical assy
	20	Bonding Strain						1.00				
	21	Module to Module alignment						1.00				
	22	Module						3.76				
	23	Distort. & misalign due to module packing							0.71			
	24	Mirror Pair Co-alignment							0.71			
	25	Mirror Pair							3.63			RSS
	26	P-S alignment in module(using CDA)								1.12		RSS
	27	CDA Dynamic Accuracy									0.50	
	28	CDA Static Static Accuracy									0.50	
	29	Thermal Drift									0.50	
	30	Focus and Coma Alignment									0.71	
	31	Reflector Installation in module								1.00		
	32	Reflector Pair (P-S)								3.30		Est based on tech dev program to date
		Color Code	Rqmt		Margin			RSS Predict		Allocation		

Derived key Observatory Pointing Requirements

1. **Attitude Knowledge:** **1.0 as**
2. **Jitter:** **+/- 0 2 arcsec = +/- 0.02 mm in X and Y**
3. **Max. X/Y displacement** (for Imaging only!) **:** **+/- 30 arcsec = +/- 3 mm in X and Y**
4. **Defocus:** **+/- 0.5 arcsec => +/- 0.3 mm in Z** (assuming a conservative f(6) beam)

Note: at 20m focal length 10 as =~ 1 mm

Mission Systems Requirements -> Error Budgets

Example: Observatory Level Pointing Knowledge Budget - Top Layer

Image Reconstruction Boresight Pointing Radial Knowledge

Radial Requirement	Expected Performance
1 arcsec radial (3σ)	.88 arcsec radial (3σ)

Observatory Properties

RSS

Rear Knowledge Error (i.e. TADS Error)

Sub-allocated Requirement	Expected Performance
.75 arcsec radial (3σ)	.70 arcsec radial (3σ)

Forward Knowledge Error (i.e. Star Tracker E-E Knowledge)

Sub-allocated Requirement	Expected Performance
.6 arcsec radial (3σ)	.54 arcsec radial (3σ)

Jitter (outside of TADS bandwidth)

Sub-allocated Requirement	Predicted Performance
.36 arcsec radial (3σ) *(0.2 arcsec radial [HPD])*	.036arcsec radial (3σ) *(0.02 arcsec radial [HPD])*

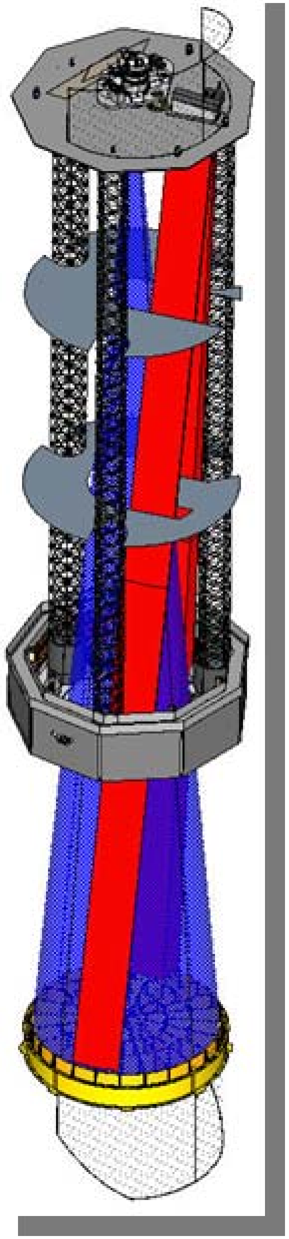
Key Observation and Payload Requirements Flow Down to Mission Systems Requirements

- **Image Quality Requirements** *>>> Pointing Control >>> GN&C, Structure, Mechanisms*
- **Image Positioning Requirements** *>>> Pointing Control*
- **Aspect Knowledge Requirements** *>>> Pointing Knowledge >>> TADS*
- **Science Observations Environment Requirements** *>>> L2 Orbit*
- **Mission Resource Constraints** *>>> LV Requirements*
  - **Fairing** *>>> Deployable Metering Structure*
  - **Throw Mass** *>>> Key Trades Attribute*
  - **Launch Dynamics** *>>> Natural Frequencies >>> Structure, Control System*
- **L2 Orbit Determination Requirements** *>>> Stationkeeping >>> Solar Momentum Management >>> Prop and GN&C >>> CP/CM offset*
- **L2 Environment (Micrometeorite Threat , Constant sun, Differential charging, etc.)** *>>> Shroud, Thermal, EPS*
- **Science Payload Complement (i.e. Instruments)** *>>> Moveable Platform*
- **Science Products Requirements** *>>> Con Ops*
- **Mission Life** *>>> Consumables sizing, Reliability, etc.*
- **Mission Success Requirements** *>>> Failure tolerance, Reliability*
- **Science Data Volume** *>>> C&DH, RF Comm*

Top IXO System Drivers, in order of Impact

1. X-ray Beams Layout (20m / 3m dia focused and dispersed beams passing thru Observatory core)
   - **Strongest driver** for IXO (size, looks, layout, and all): drives the Fixed and Deployable Metering Structures' length and diameter, calls for a "ring" type S/C Module in the middle, etc.
   - **Strong** driver for a host of unique IXO problems and solutions: Flexbody issues and related Rear Pointing Knowledge issues (TADS), Micrometeorite issues (Whipple shield), CP/CG issues (S/A Layout, Thruster configuration, etc), Observatory MOI issues (ACS / Reaction Wheels, Thrusters), etc.
2. Instrument Module Mass
   - A **strong** driver for sizing the Fixed Metering Structure strength *(for Launch Loads)*
   - A **strong** driver for the ADAM Mast implementation *(quantized in crude increments: 1, 2, or 3 masts, and mast strength)*
3. FMA Mass
   - A big mass to lift in itself, the FMA positioned **MASS as the premier trade criterion** in most trades
   - **Strong** driver for the FMA Thermal System *(complete with Body Mounter Solar Arrays, Regulators, etc.)*
   - Biggest contributor to Observatory MOI, hence a **strong** driver for ACS / Reaction Wheels
4. General capabilities required of a Class B Great Observatory
   - **Strong** driver for every Subsystem, such as data handling, propulsion, pointing, RF comm, etc.; for redundancy / reliability, etc.

- *__Important to remember:__ When a subsystem is driven to an increase, the chain of events doesn't stop there. That increase might drive other subsystems to increase, which in turn does the same to yet other subsystems, and so forth. This circum-driving series is usually convergent and settles out, but in some unfortunate cases it may be divergent and may break the design.*



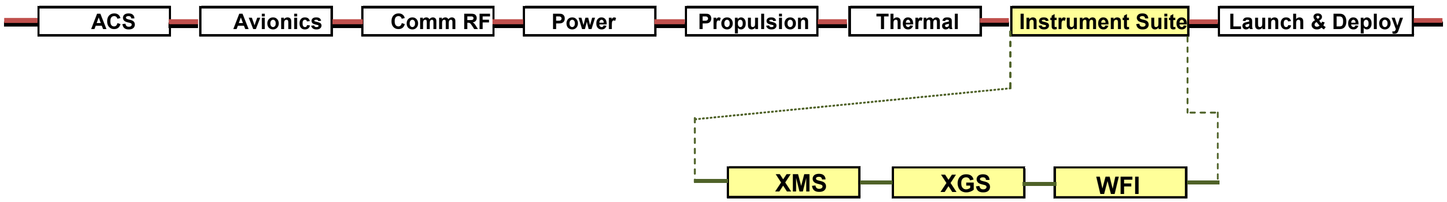
Mission Assurance Requirements

Risk Classification for NASA Payloads from NPR (NASA Procedural Requirements) 8705.4

Characterization	Class A	Class B	Class C	Class D
Priority (Criticality to Agency Strategic Plan) and Acceptable Risk Level	High priority, very low (minimized) risk	High priority, low risk	Medium priority, medium risk	Low priority, high risk
National significance	Very high	High	Medium	Low to medium
Complexity	Very high to high	High to medium	Medium to low	Medium to low
Mission Lifetime (Primary Baseline Mission	Long, >5years	Medium, 2-5 years	Short, <2 years	Short < 2 years
Cost	High	High to medium	Medium to low	Low
Launch Constraints	Critical	Medium	Few	Few to none
In-Flight Maintenance	N/A	Not feasible or difficult	Maybe feasible	May be feasible and planned
Alternative Research Opportunities or Re-flight Opportunities	No alternative or re-flight opportunities	Few or no alternative or re-flight opportunities	Some or few alternative or re-flight opportunities	Significant alternative or re-flight opportunities
Achievement of Mission Success Criteria	All practical measures are taken to achieve minimum risk to mission success. The highest assurance standards are used.	Stringent assurance standards with only minor compromises in application to maintain a low risk to mission success.	Medium risk of not achieving mission success may be acceptable. Reduced assurance standards are permitted.	Medium or significant risk of not achieving mission success is permitted. Minimal assurance standards are permitted.
Examples	HST, Cassini, JIMO	MER, MRO, Discovery payloads, ISS Facility Class Payloads, Attached ISS payloads	ESSP, Explorer Payloads (MIDEX, SMEX), ISS complex subrack payloads	SPARTAN, GAS Can, technology demonstrators, simple ISS, express middeck and subrack payloads

Reliability

- Mission success criteria: 85%
  - XMS, XGS, and WFI, are required to be operational for a successful mission



	Reliability Assessment At 5 years	Reliability Assessment At 10 years
Spacecraft Bus Sub-Systems		
ACS	0.9845	0.9572
Avionics	0.9946	0.9796
Comm RF	0.9929	0.9838
Power	0.9993	0.9974
Propulsion	0.9926	0.9865
Thermal	0.9868	0.9486
SC	0.9516	0.8610
Instrument Suite		
XMS	0.9763	0.9497
XGS	0.9711	0.9389
WFI	0.9711	0.9389
IS	0.9207	0.8372
Solar Array Deployment	0.9747	0.9747
Overall Reliability [SC. IS, L&D]	0.85	0.70

Driving Aspects of Observatory Design

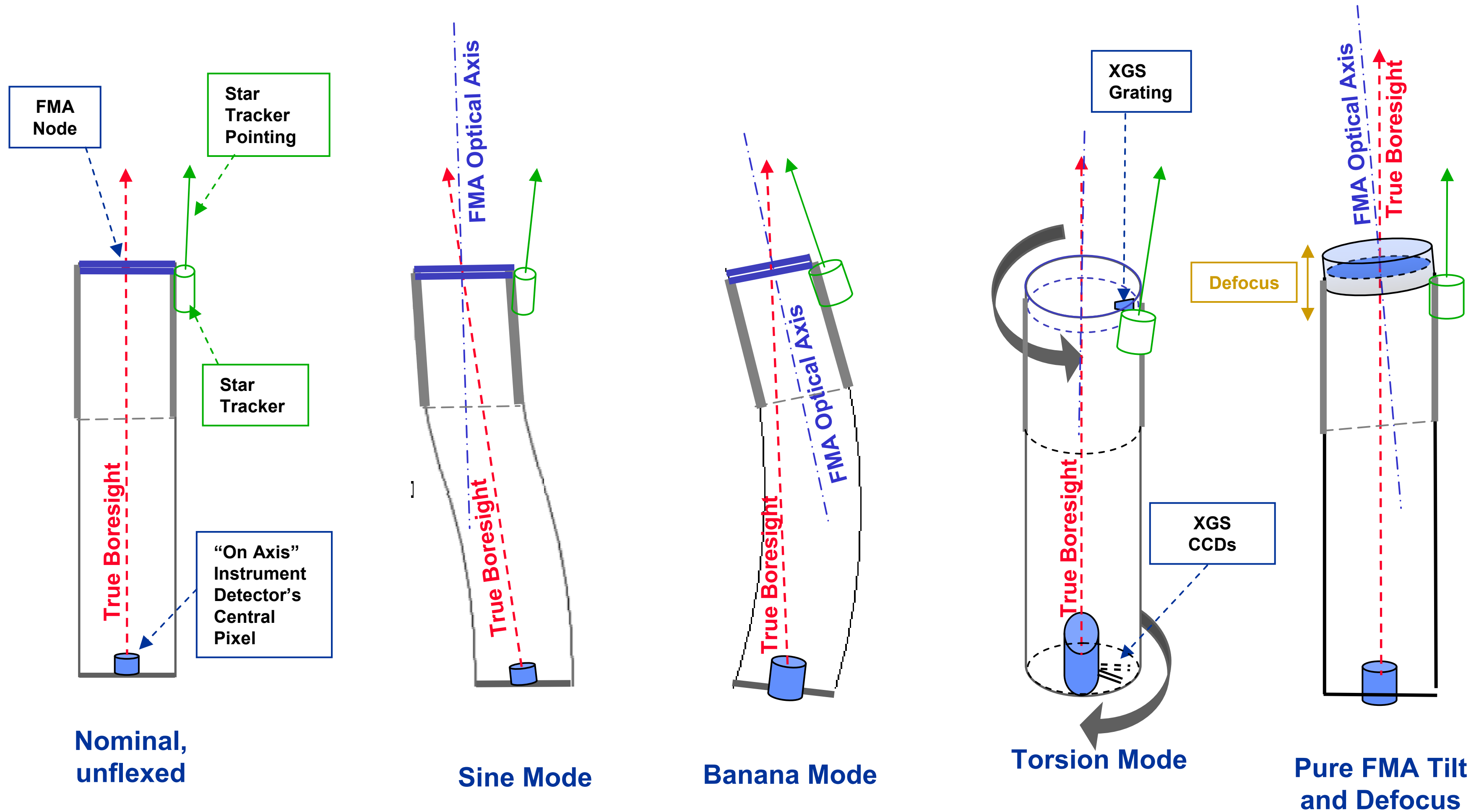
Significant Aspects of Observatory Design

The following slides show an overview of some of the challenging aspects of the IXO design, namely:

1. **Flex Body Effects and Structural Misalignments**
2. **Two Proposed Gratings Concepts**
3. **Beams through Observatory Core**
4. **Deployment Module and Whipple Shield Shroud**
5. **Attitude Disturbance from Solar Torque Offloading**

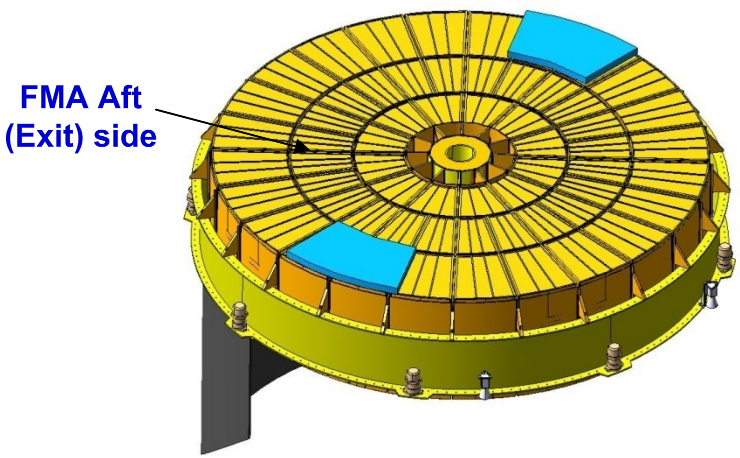
1. Flex Body Effects and Structural Misalignments

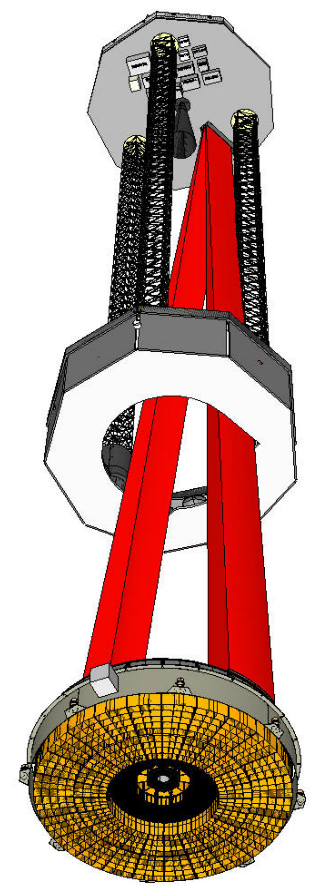
Boresight to Star Tracker and Boresight to FMA Optical Axis Misalignments

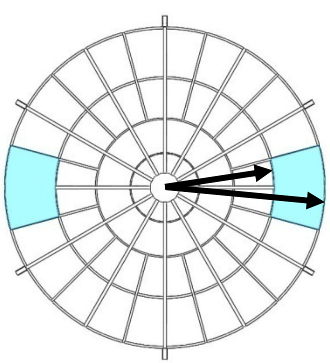


2. Two Gratings Concepts: FMA w/ CAT XGS Gratings Assy

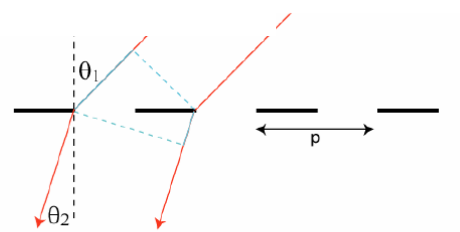
- Optics Module consists of the Flight Mirror Assembly (FMA), High Energy Telescope (HXT), FMA interior cover, FMA exterior cover, XGS gratings, spacecraft adapter, deployable sunshade, launch vehicle separation system, and star trackers.
- 3.24 m outer diameter of FMA, 3.36 m outer diameter of spacecraft adapter.
- HXT is located in the center of the FMA.







1125 mm ID
1630 mm OD
30 deg arc



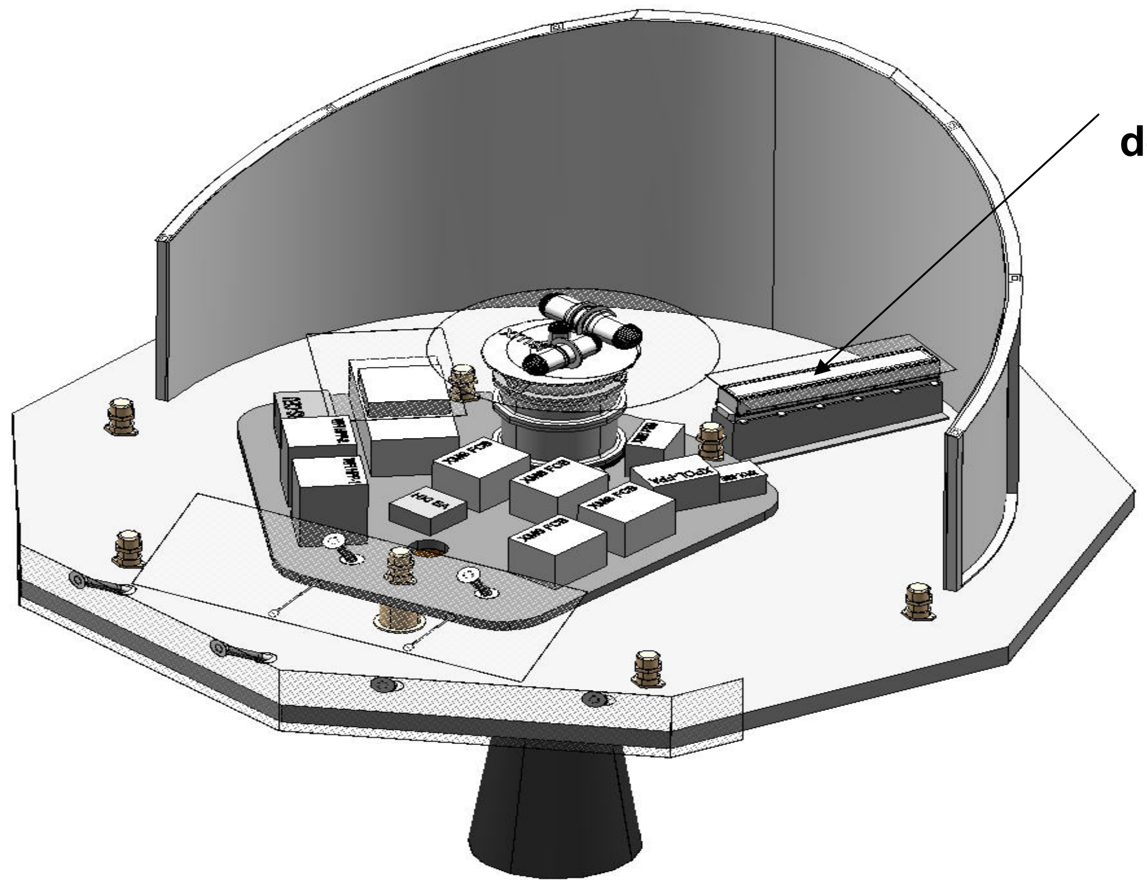
path length difference (PLD) = $p(\sin\theta_1 - \sin\theta_2)$
constructive interference: PLD = $m\lambda$

Grating Equation:

$$m\lambda = p(\sin\theta_1 - \sin\theta_2)$$

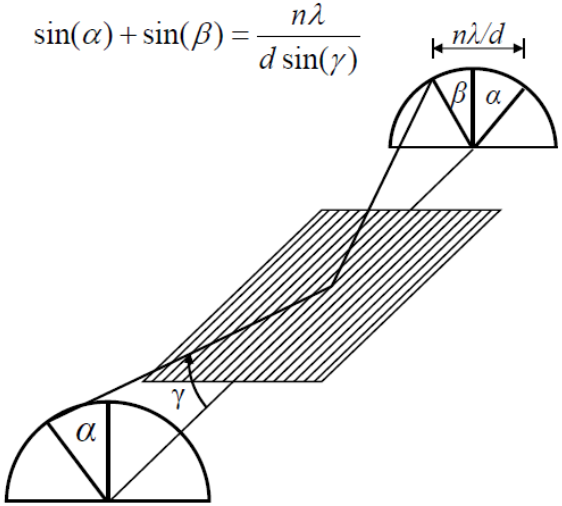
2. Two Gratings Concepts: Instrument Module with CAT XGS Camera (Radial Layout)

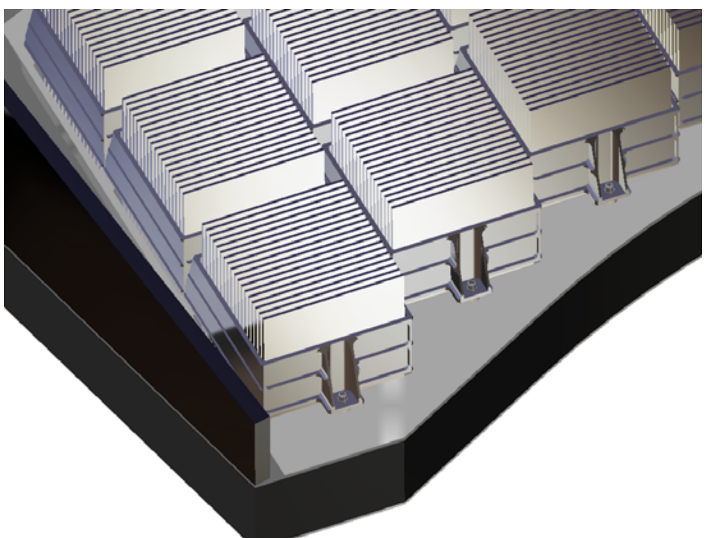
XGS (CAT) Camera: Radial CCD Array layout clocked 30 degrees off the "X" axis

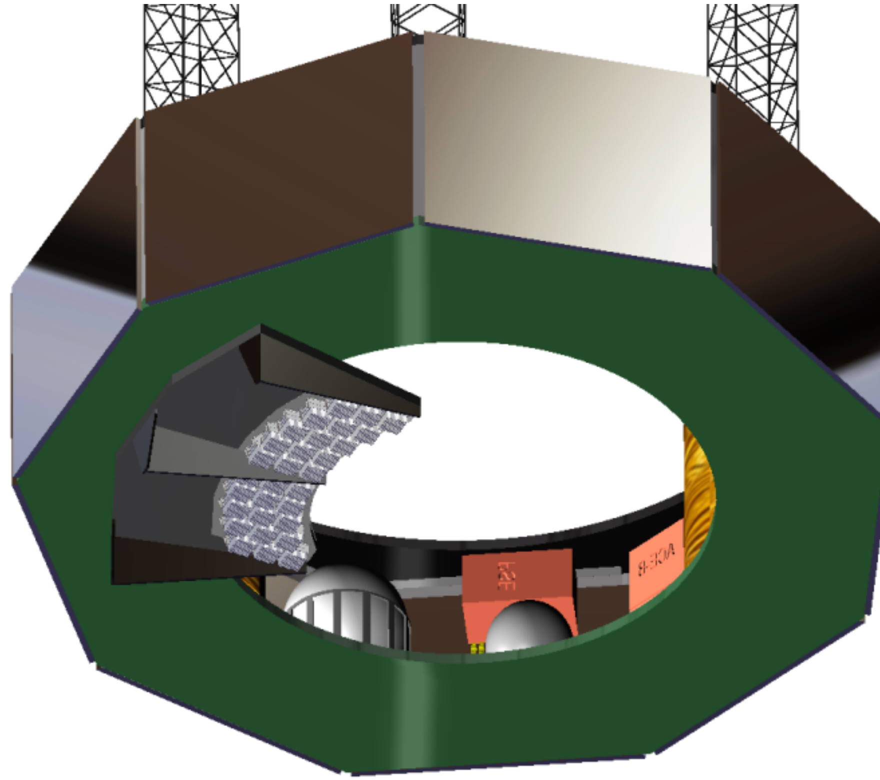


2. Two Gratings Concepts: S/C Module with Off-Plane XGS Gratings Assy

$$\sin(\alpha) + \sin(\beta) = \frac{n\lambda}{d\,\sin(\gamma)}$$

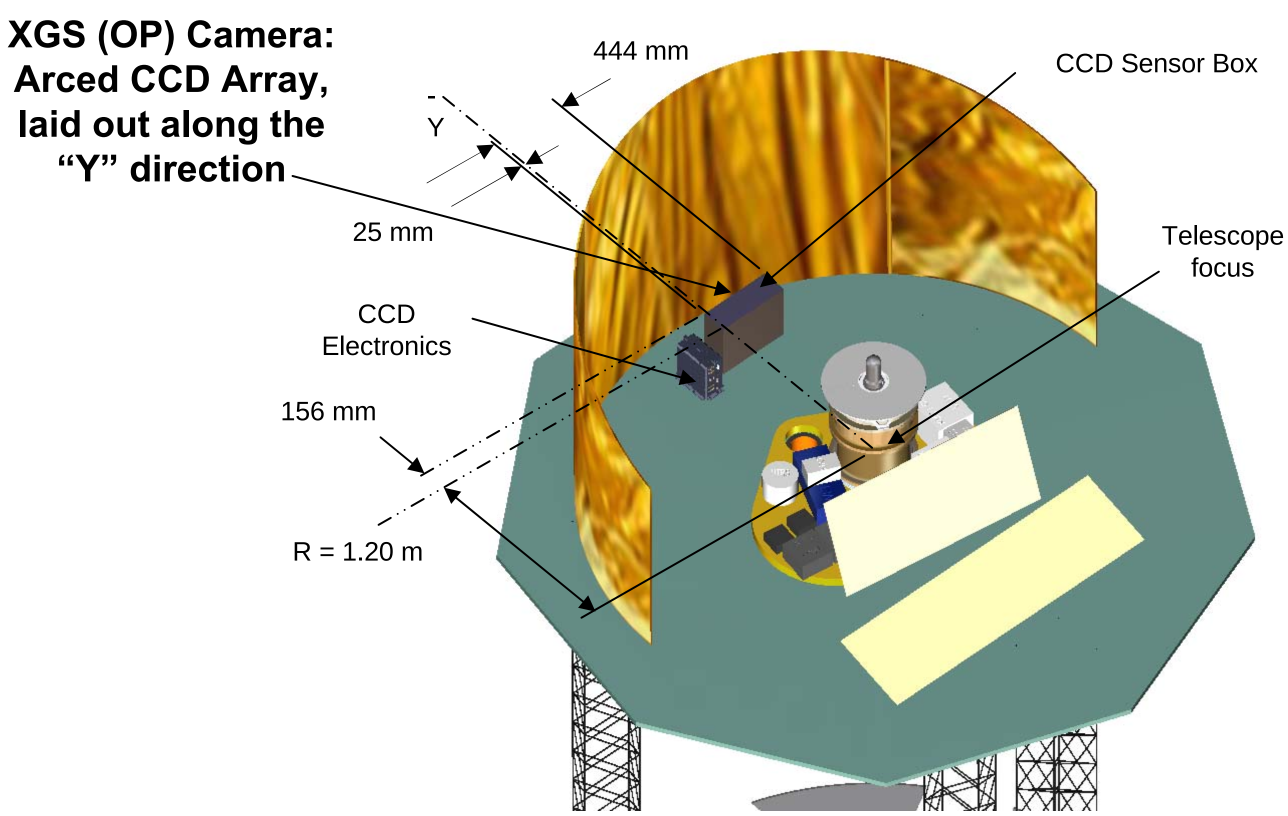


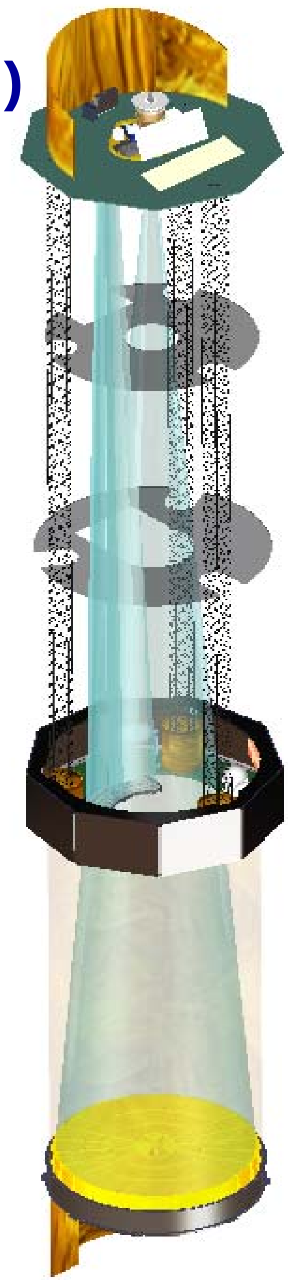




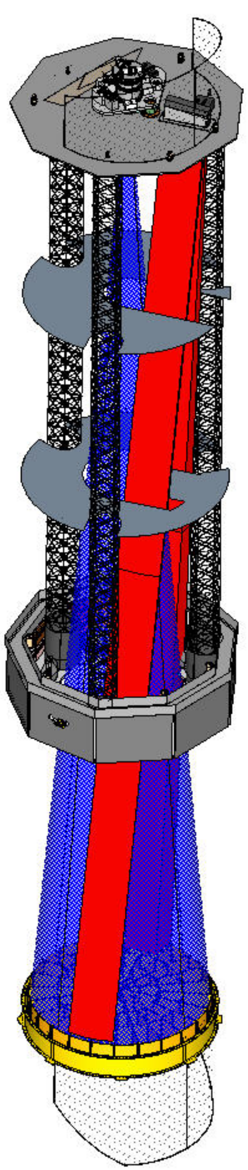
Grating Mirror Assembly Platform mounted to S/C Platform 13.5 m from telescope focus

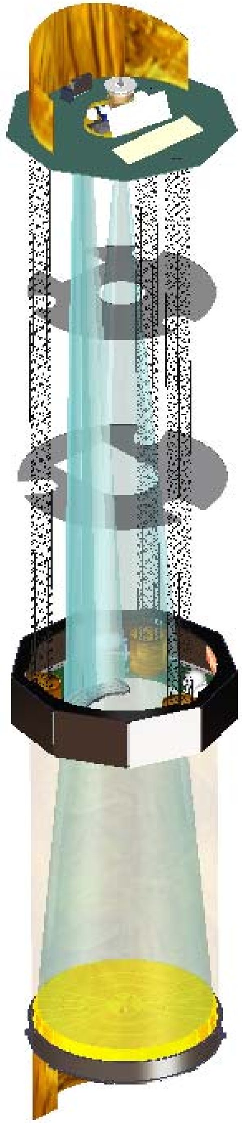
2. Two Gratings Concepts: Instrument Module with Off-Plane XGS Camera (Tangential Layout)



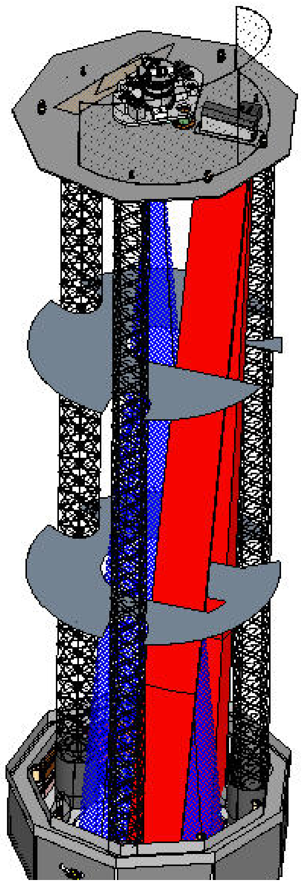


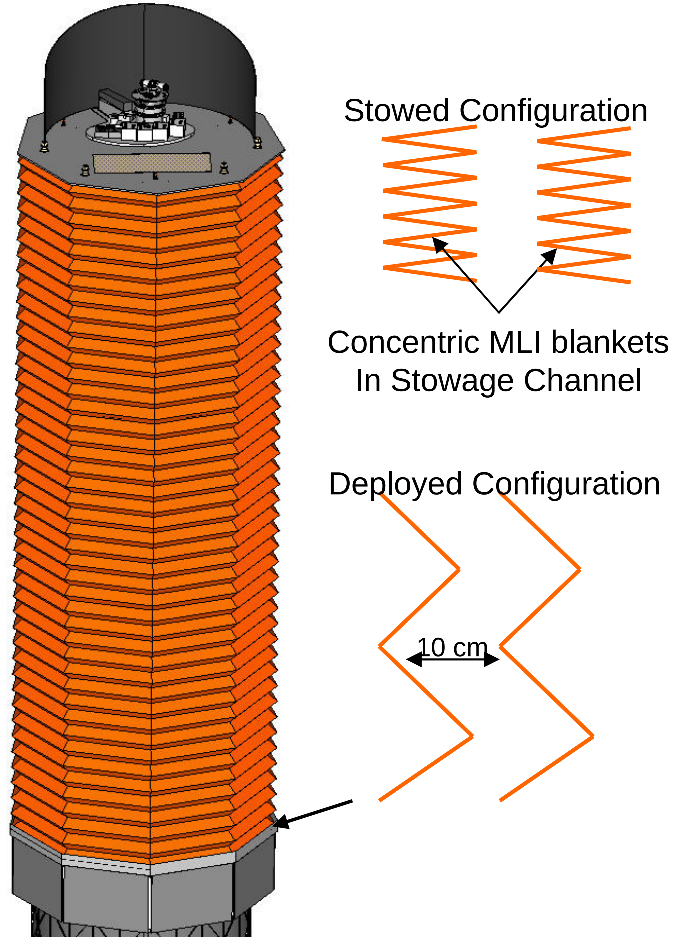
3. Beams thru the Observatory Core for the two proposed gratings concepts



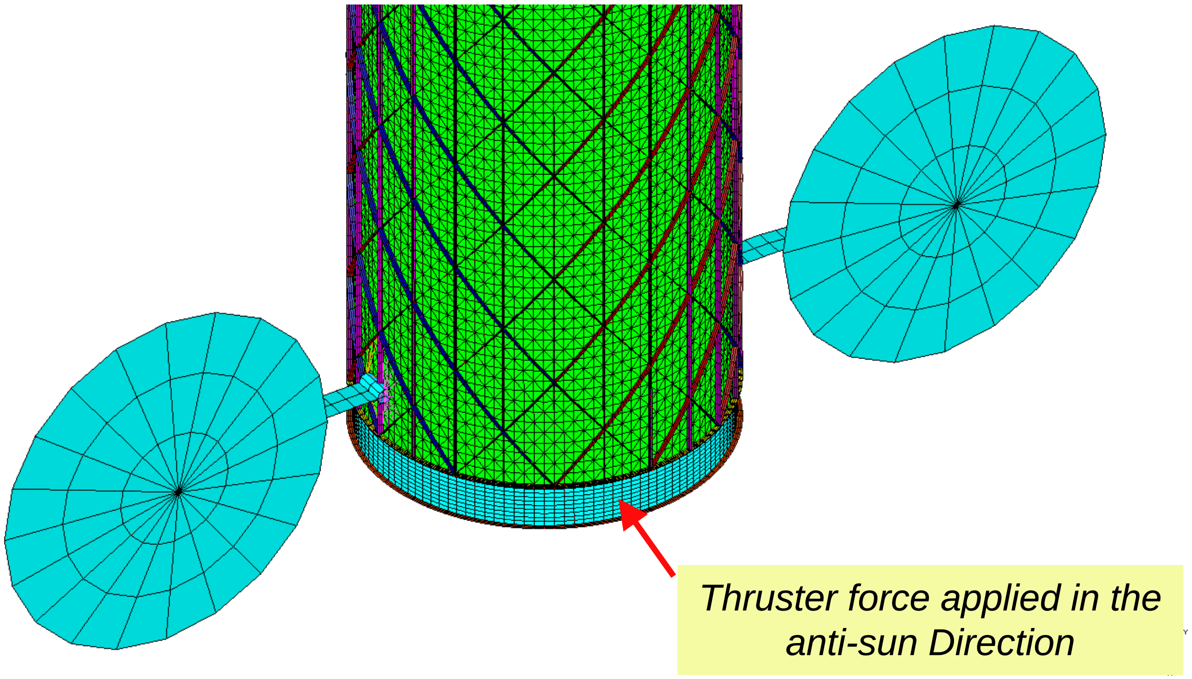


4. Deployment Module with Deployable Whipple Shield Shroud





5. Solar Torque Offloading with 0.9N Thruster Pulses



- **Use highly reliable MR103H Aerojet monoprop thrusters used for Voyager and Cassini, applying micro-pulses ever 18 minutes**

Contingency Functions Trades

Contingency Functions

Several failsafe and contingency mode functions were considered as part of the IXO design:

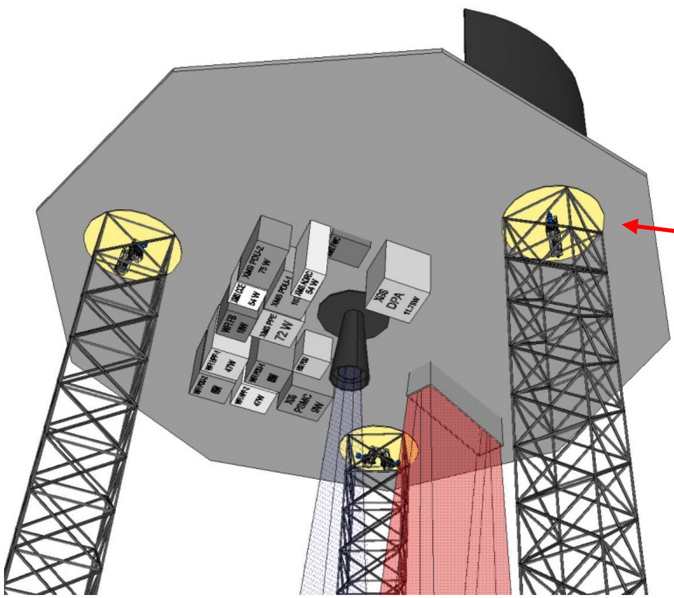
- **Focus and Translation Mechanisms**
  - **Focus (+/-Z) Mechanism for XMS and WFI/HXI**
  - **Focus (+/-Z) Mechanism for the XGS (both CAT and OP)**
  - **Cross-dispersion direction Translation Mechanism for the OP XGS (+/-X)**
- **Implemented in Baseline Configuration**

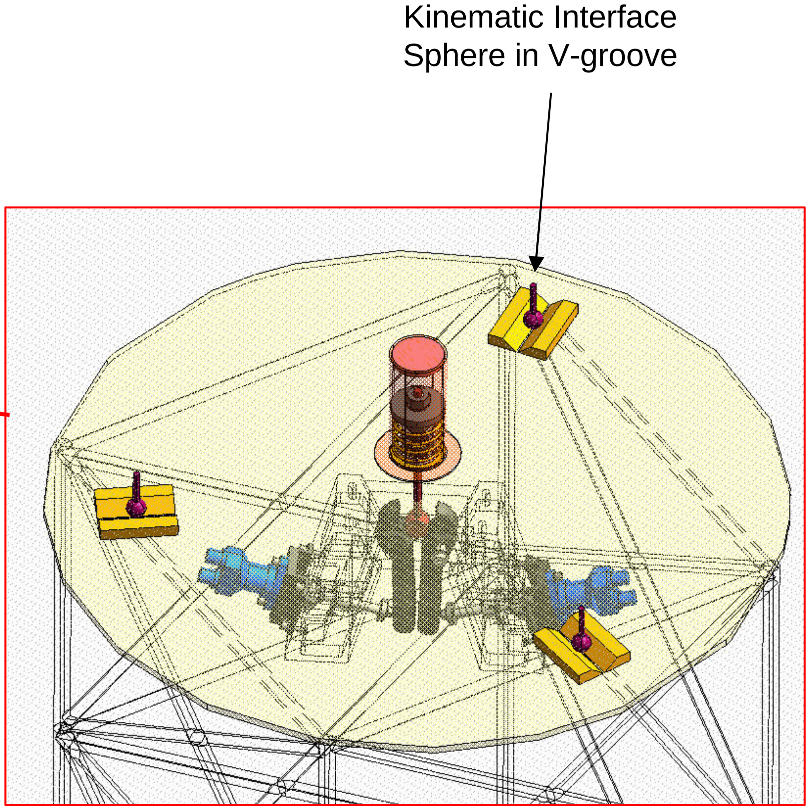
- **Mast Deployment Contingency**
  - **Disconnecting a failed mast via Kinematic FIP Mounts**
  - **Then deployment and Mission on 2 Masts**
- **Descoped from Baseline Configuration per Systems Review recommendation**

- **MIP Independent Failsafe Rotator:**
  - **In case of main drive failure, rotates MIP with Instrument in viable Science position**
- **Descoped from Baseline Configuration per Systems Review recommendation**

Mast Deployment Contingency: Kinematic FIP Mounts

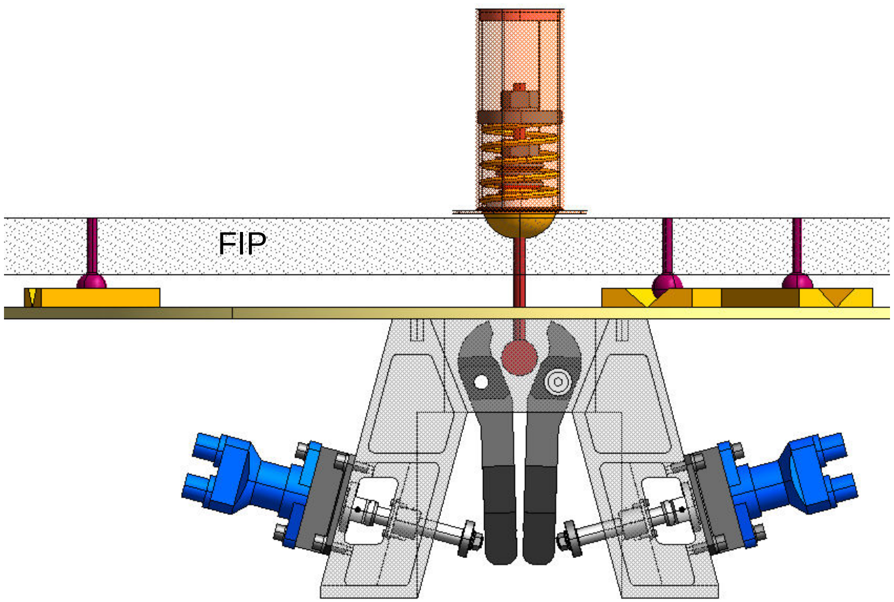
- Three spheres which are screwed into the FIP are compressed into V-grooves on the ADAM plate.
- This kinematic joint provides repeatable placement of the mast onto the FIP as well as providing point contact between the separating parts.
  - Point contact simplifies separation and minimizes the force required.



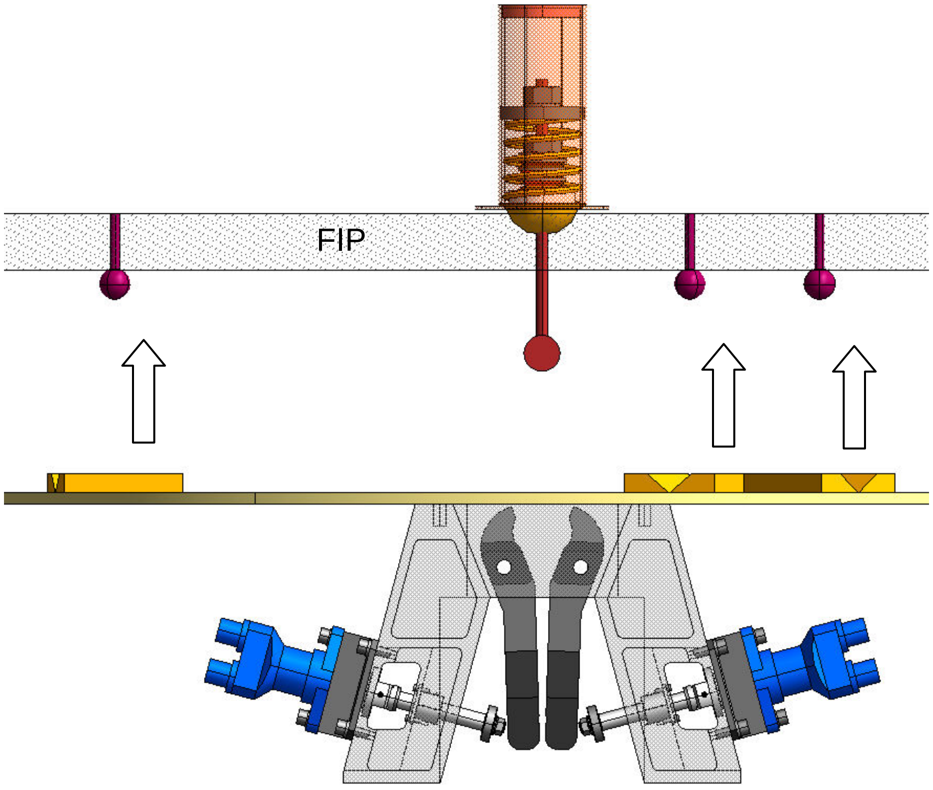


Deployment on 2 Masts: Disconnecting a Failed Mast

- **NSI pyros on each sep nut fire. Only one latch jaw is required to rotate to free the latch pin. After the jaws open, the FIP is disconnected from the mast and is free to move upwards as the other masts deploy.**



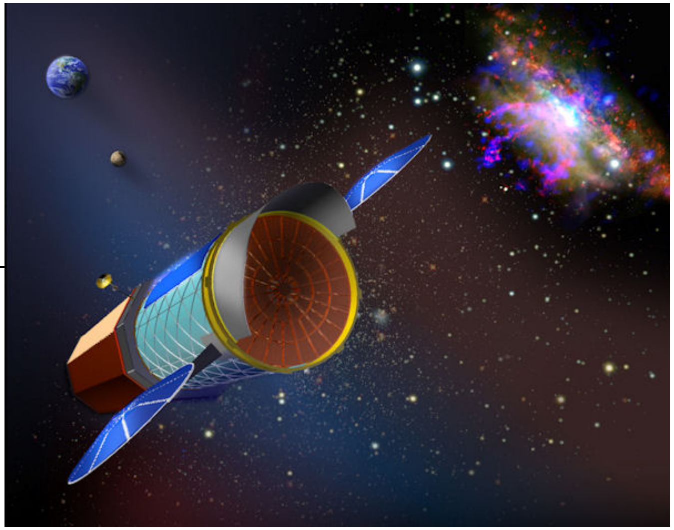
Latch jaws open



FIP is disconnected from failed ADAM mast

IXO Systems Definition Document
Chapter 3

Mechanical Systems



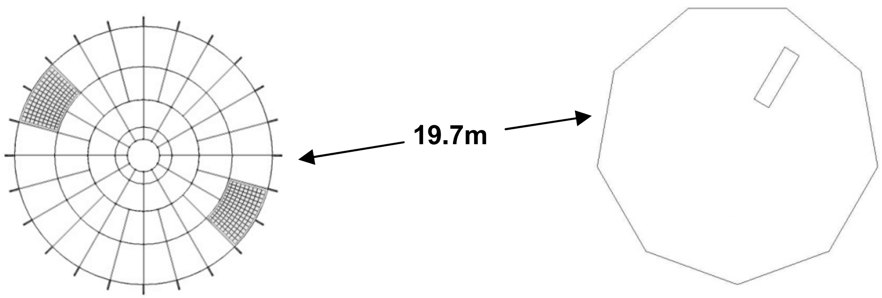
Requirements and Design Drivers

Six primary requirements drive the mechanical configuration of the observatory:

1. **IXO shall have a 20 meter focal length**
   - Drives the need for a deployable instrument module
   - X-ray beams make a very large keep out zone inside the observatory
2. **X-ray collecting effective area of the FMA shall be 3.0 m^2 at 1.25 keV, etc.**
   - Drives diameter of the FMA to 3.3 m which sets the minimum base diameter of the observatory.
   - The mass of the FMA favors its placement near the launch vehicle to keep the CG low.
   - 3.3m diameter FMA favors the use of a large truss adapter instead of a PAF.
3. **Instrument accommodations**
   - Drives the IM thermal design (sunshade, heat pipes, radiators)
   - Drives need for moving platform (MIP) so instruments share time at the focal plane
4. **IXO shall launch on an EELV or Ariane V launch Vehicle**
   - Envelopes the volume and mass of the observatory, sets loads & modes
5. **IXO shall have an L2 orbit**
   - Sets the throw mass of the launch vehicle
   - Sets the thermal environment (quiescent, cold)
6. **IXO shall have tight sub-arcsecond spacecraft pointing, alignment, and stability**
   - There is a budget for these items which will not be detailed here.
   - Drives use of near-zero CTE CFRP composites where possible
   - Drives the use of fine-focusing and translation stages on many instruments
   - Drives the selection of the deployment system to one that is stable, accurate, stiff.
   - Limited pitch & roll helps in the thermal area, and sets the size of the sunshades

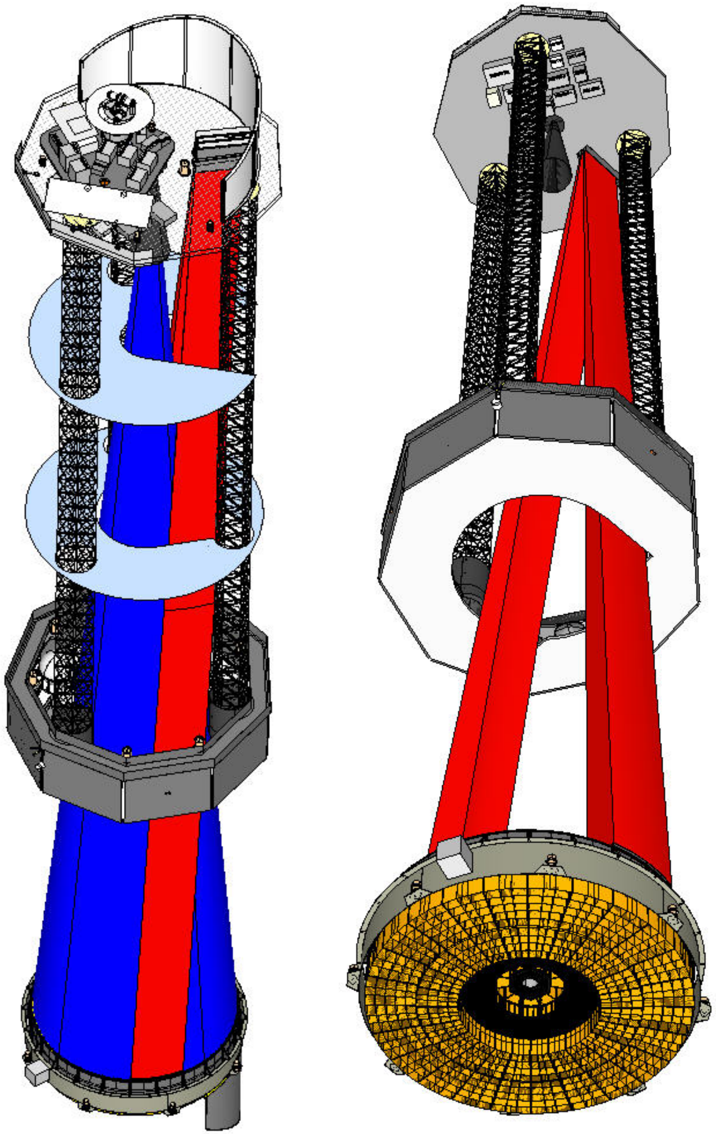
X-ray Beams Drive the Design

- The X-ray traces of the FMA and XGS traverse nearly the entire length of the observatory.
- The FMA beam is a 20 m long cone with 3.3m base diameter, originating at the FMA node. It ends at the focal point.
- The XGS X-ray beams transition from a wedge shape on the aft of the FMA to a 780mm long line at their focus, with an offset of 720 mm from the FMA optical axis.
- XGS x-ray beams determine the clocking of the masts, gratings, and XGS camera.



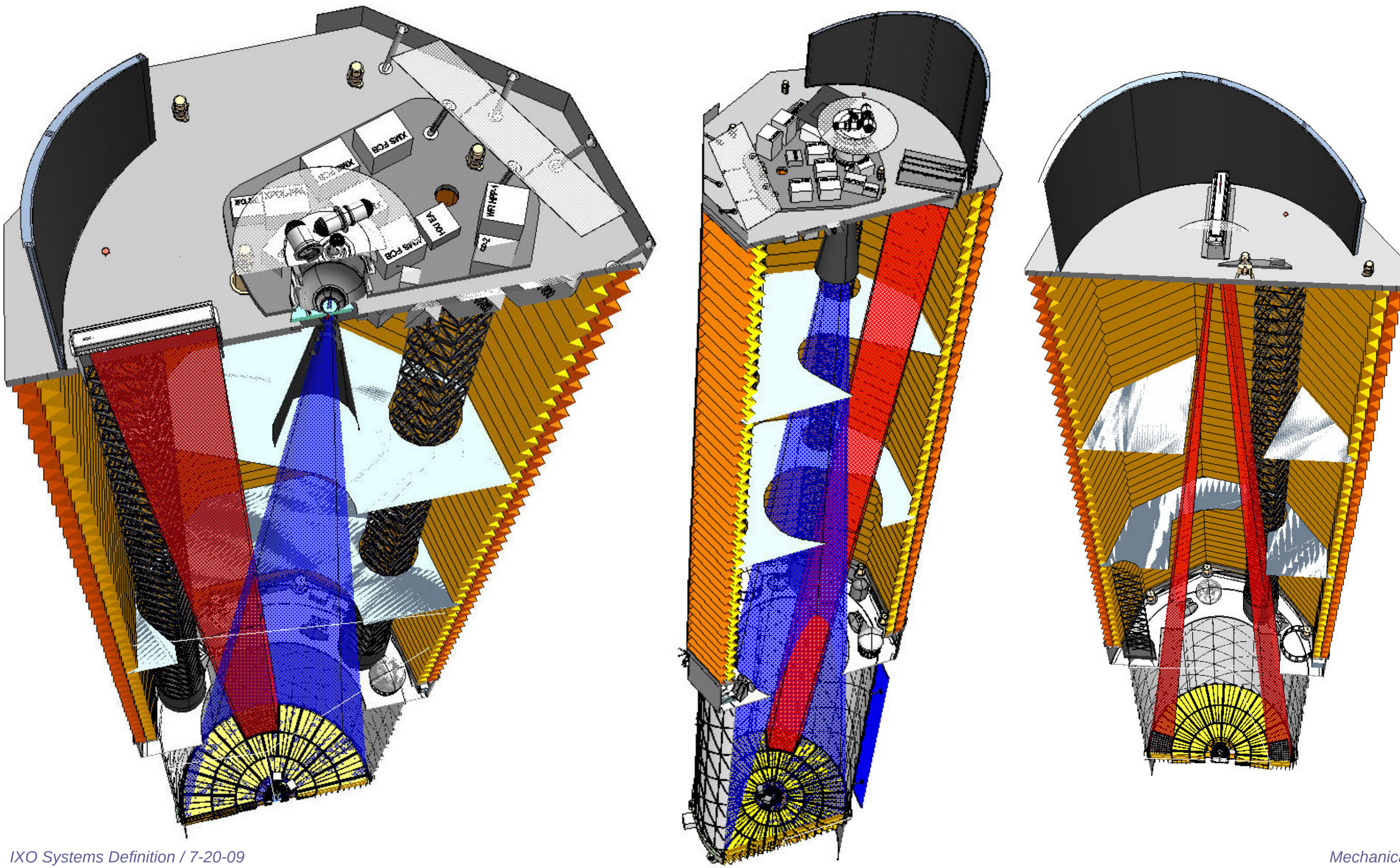
FMA with gratings

FIP with CCD camera



FMA X-rays (blue) & XGS X-rays (red)

Cutaway Views of X-ray Beams



Four Modules

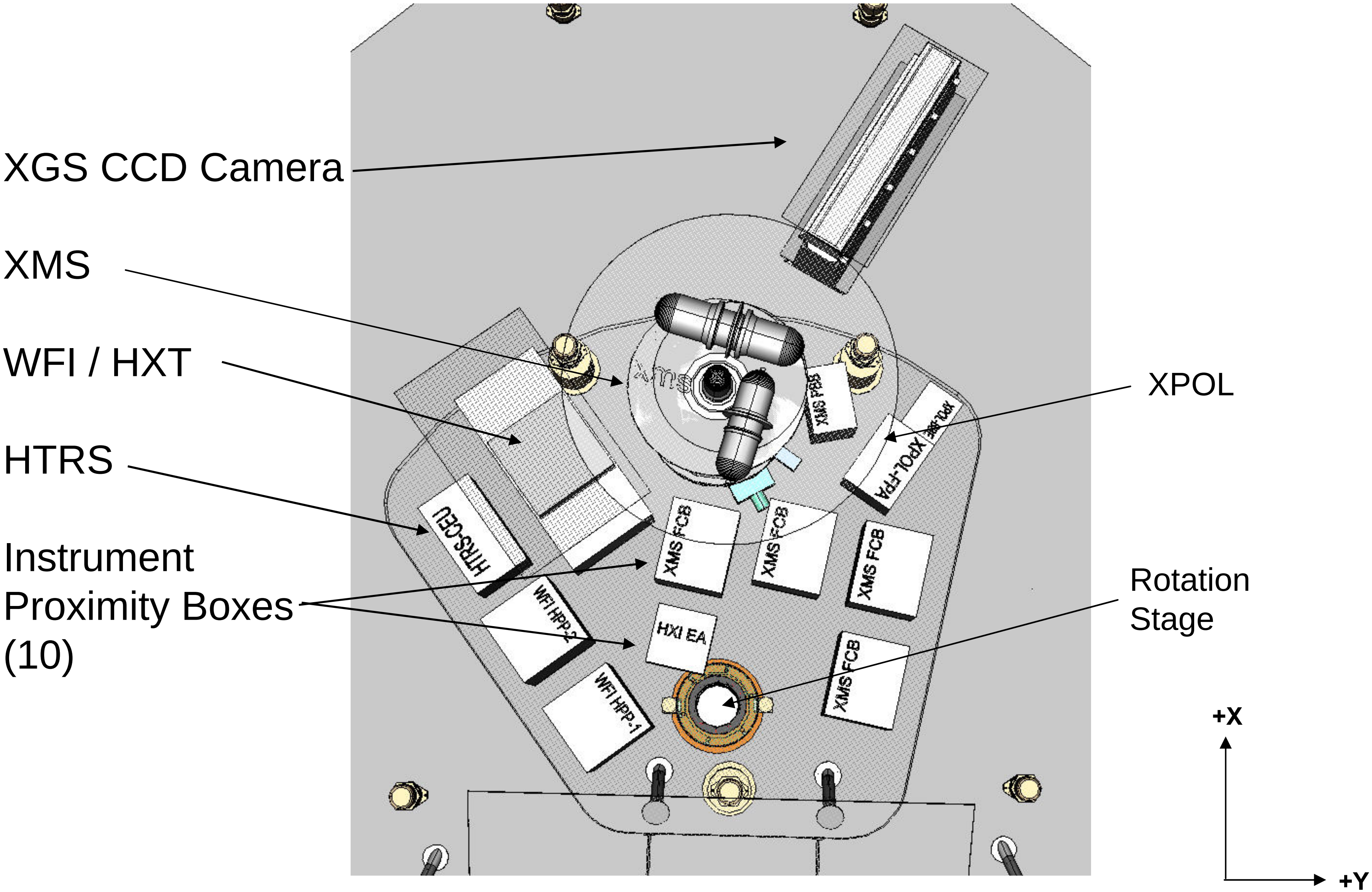
- The observatory has been formed into four modules: Optics Module, Spacecraft Module, Deployable Module, and Instrument Module.
- Each module will be a deliverable to I&T, and each will be the responsibility of a prime contractor and/or space agency.
- Each module may be fabricated, assembled, qualified independently of the others.
- Each module has its own project team, schedule, and budget.
- Interfaces between modules will be controlled via the typical ICD process during Phase A/B/C.

Instrument Module

The IM consists of the following mechanical systems

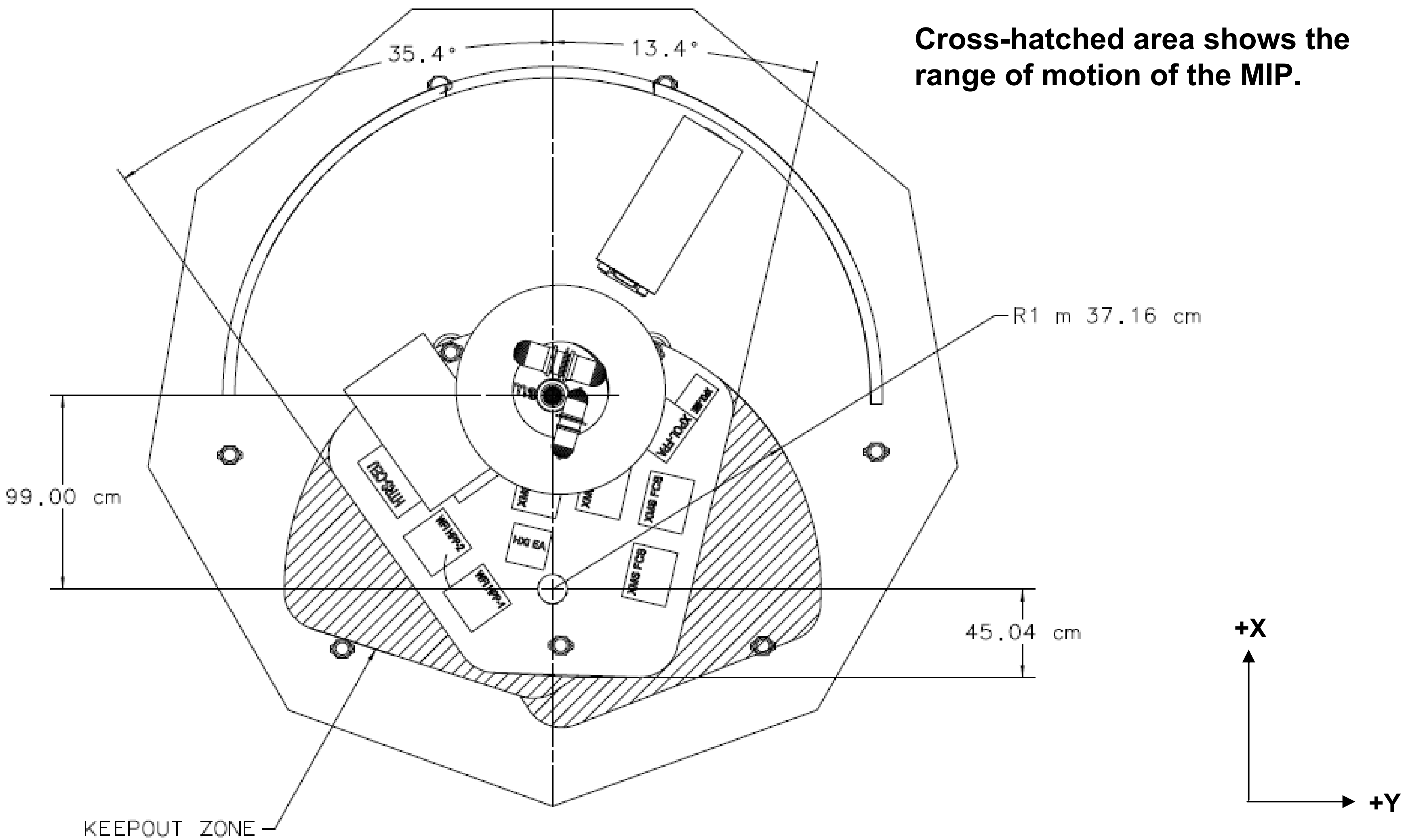
- **Instruments**
  - XMS, WFI, HXI, XPOL, HTRS, XGS Camera
- **Fixed Instrument Platform (FIP)**
  - Platform for MIP, XGS camera, many electronics boxes, sunshade
  - 9-sided 4" thick honeycomb panel, .020" aluminum facesheets
  - Embedded variable conductance heat pipes (VCHPs)
- **Moveable Instrument Platform (MIP)**
  - Platform for XMS, WFI/HXI, XPOL, HTRS instruments, and ~10 proximity electronics boxes.
  - 2" thick honeycomb panel, .020" aluminum facesheet
  - Embedded VCHPs and Rotation stage between MIP and FIP
- **Rotation Stage**
- **Common baffle attached below FIP**
  - Carbon Fiber Reinforced Plastic (CFRP) conical or cylindrical baffle to block stray light
- **Several positioning stages for instruments.**
  - XMS: focus
  - WFI/HXI: focus
  - XGS: focus and translation
- **Radiators and Struts**
  - Aluminum honeycomb radiators with embedded Constant Conductance Heat Pipes (CCHPs).
- **Sunshade**
  - Semicircular CFRP tubular frame with MLI blanket to block sunlight.
- **Launch Locks on MIP and FIP**

MIP Instrument Suite top view

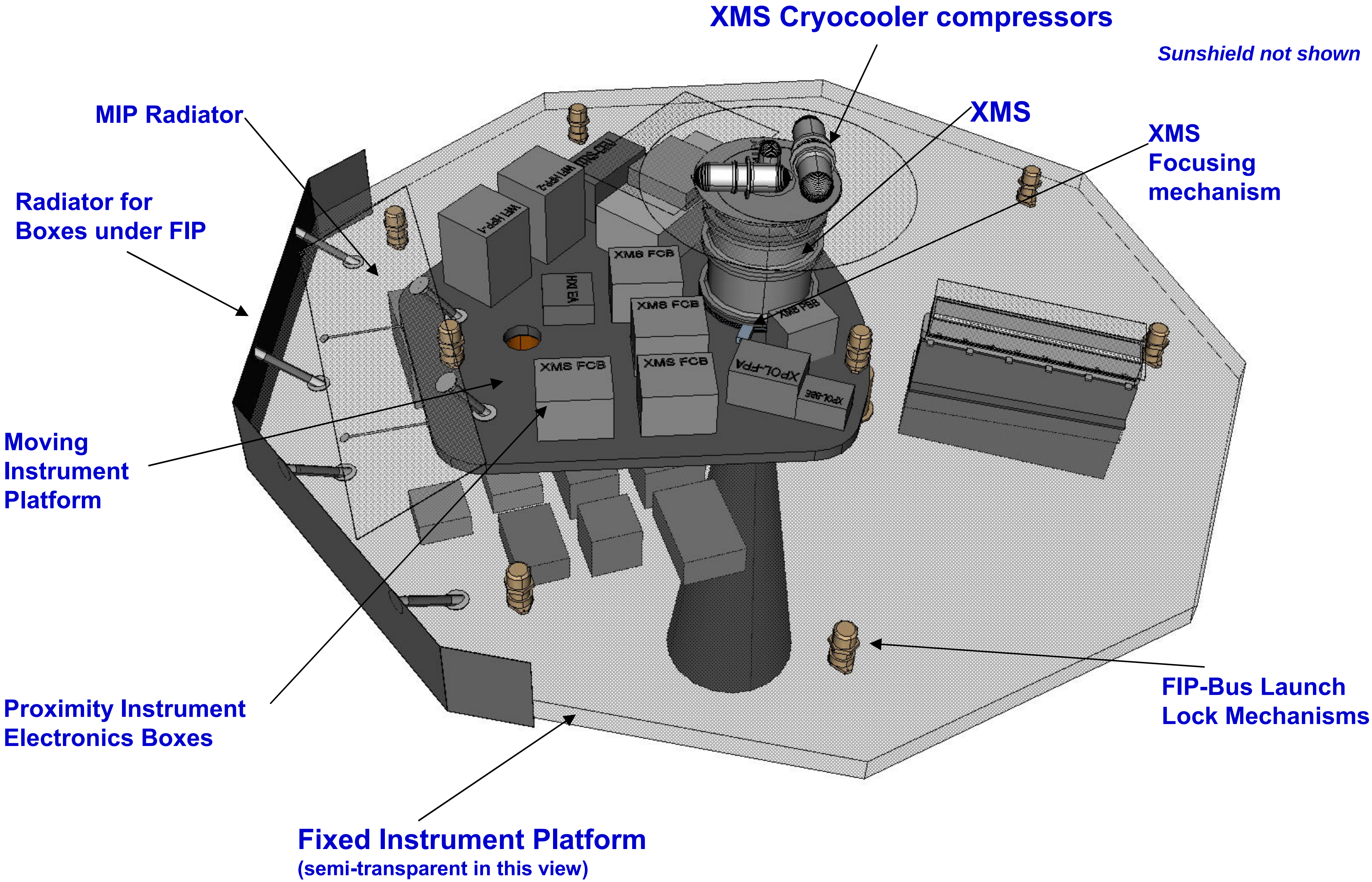


MIP Keep Out Zones

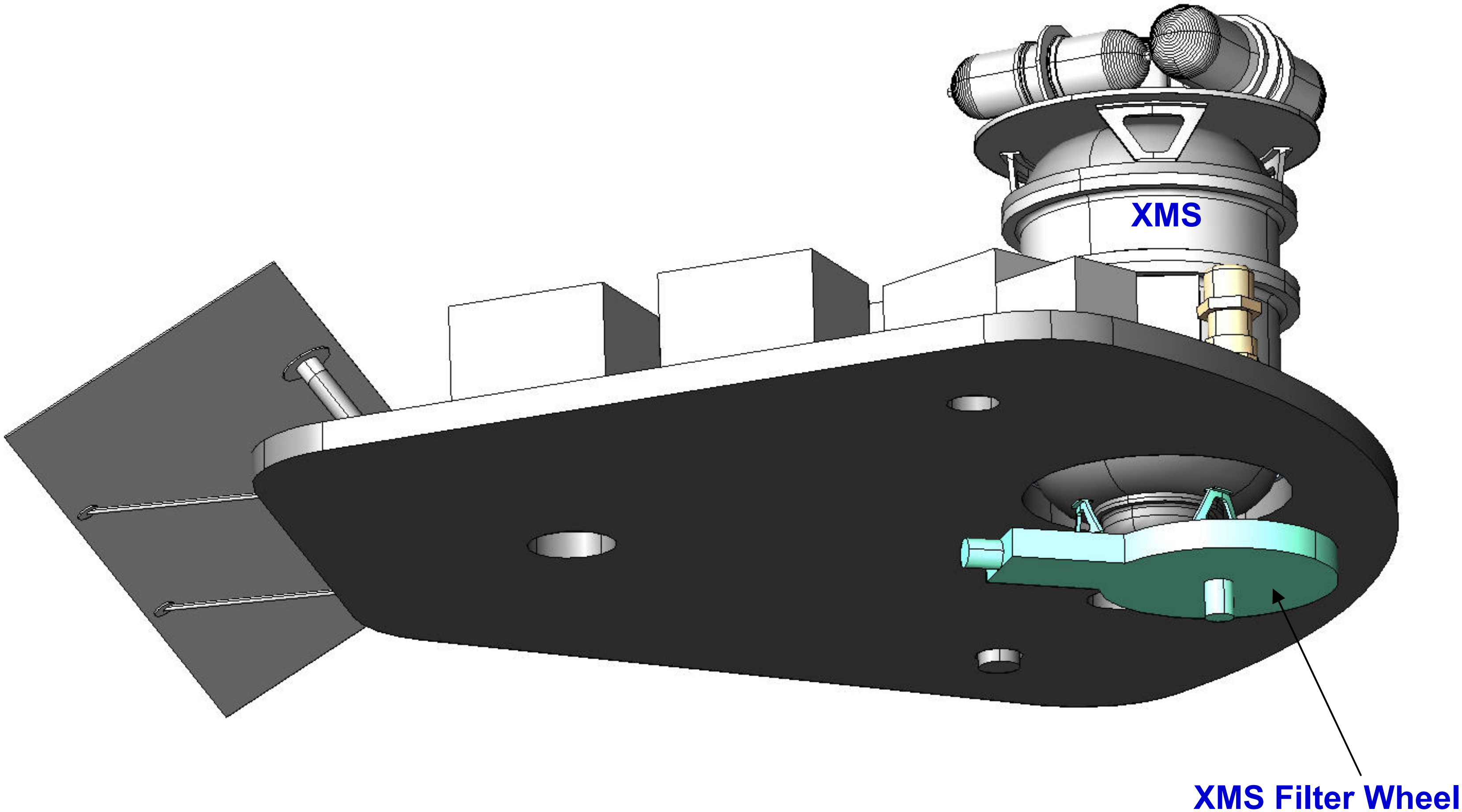
Cross-hatched area shows the range of motion of the MIP.



Instrument Module Side View

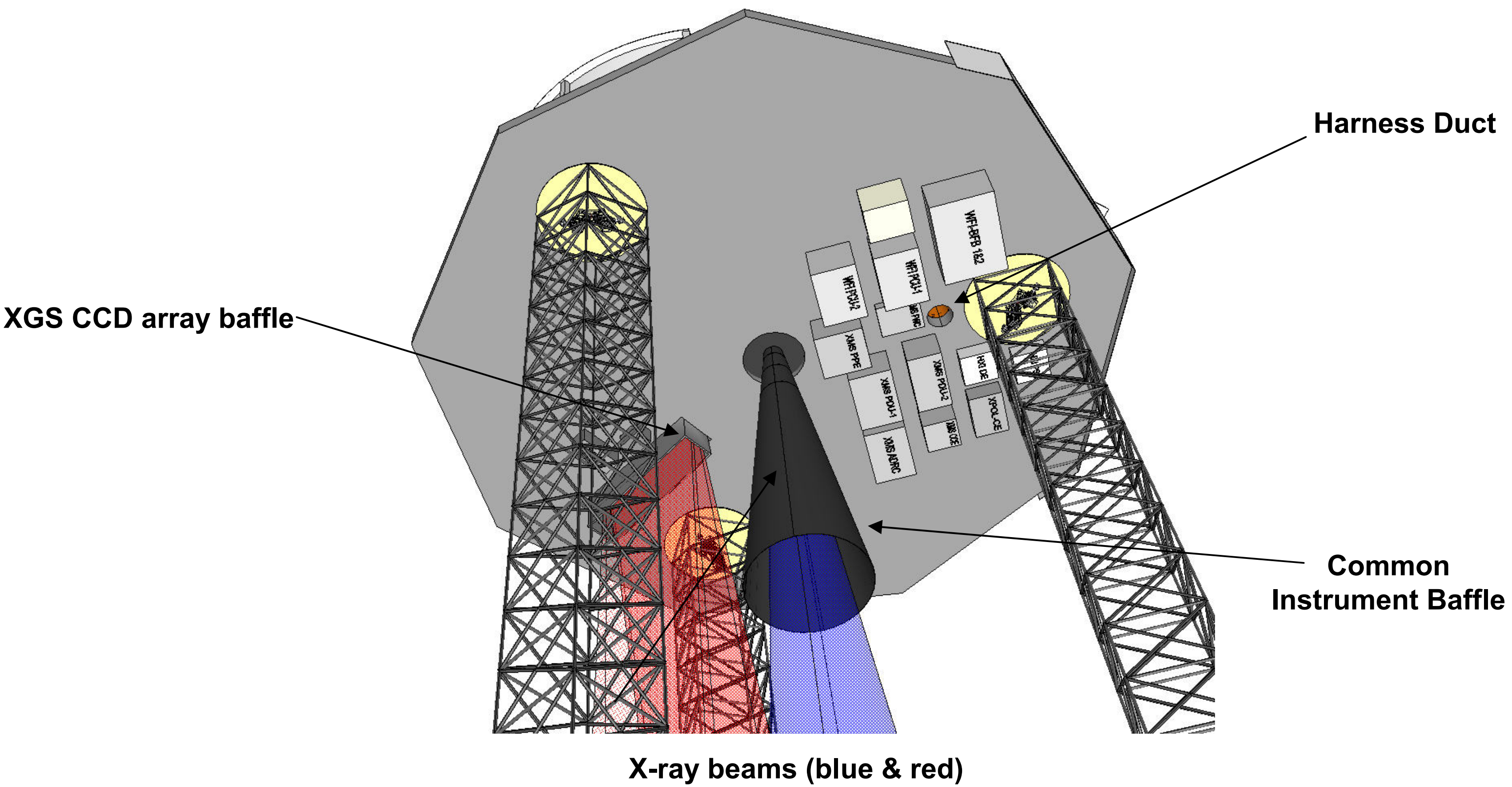


View of XMS Filter Wheel



FIP Underside

- Instrument electronics boxes that do not need to be close to the instruments are mounted on the underside of the FIP.
- Harnesses pass though the 15 cm diameter hole in the rotation stage of MIP.
- Harness from XGS Camera to its electronics box (DEA) travels through a cutout in the FIP.
- “Common instrument baffle” for XMS, WFI/HXI instruments

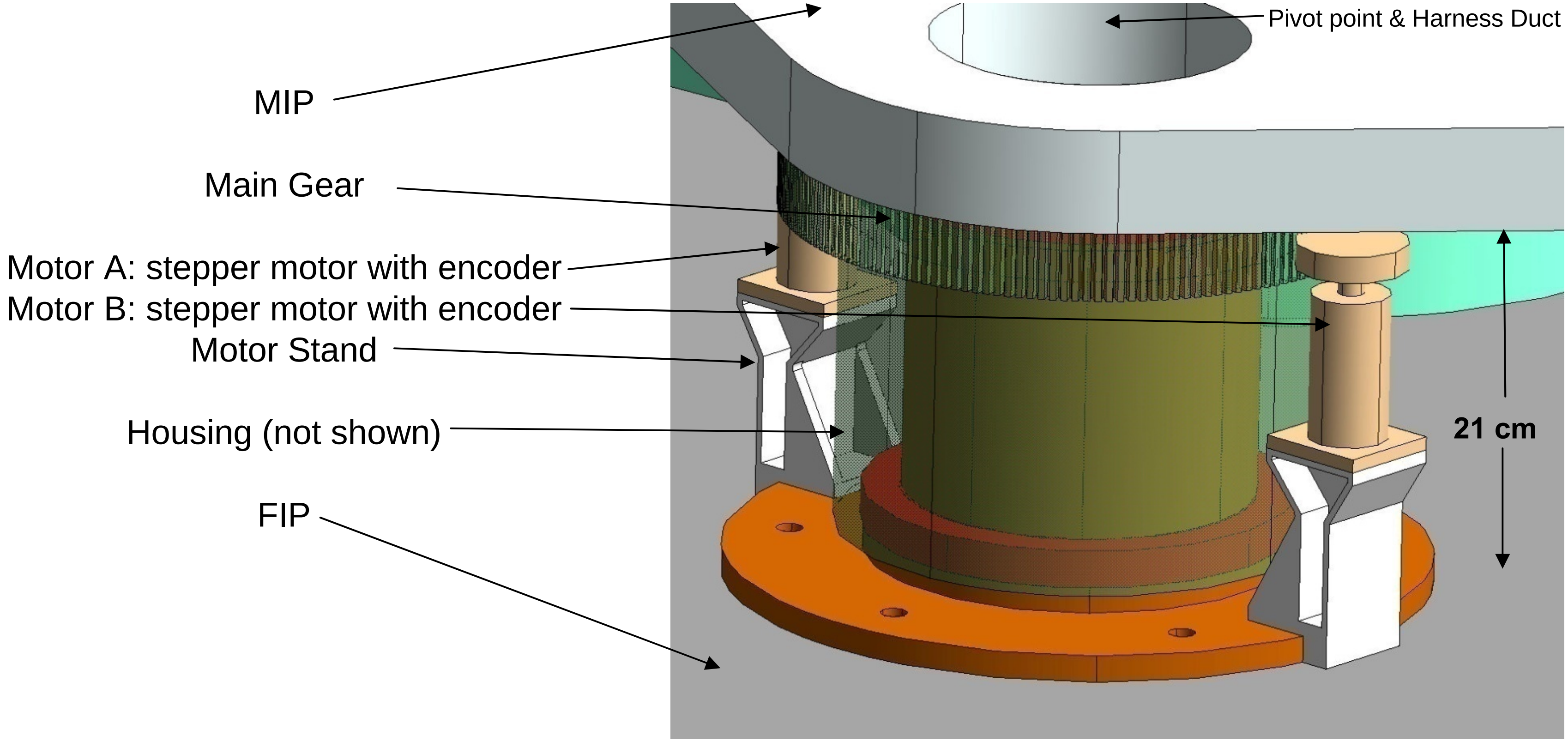


Rotation and Translation Stages, Launch Locks

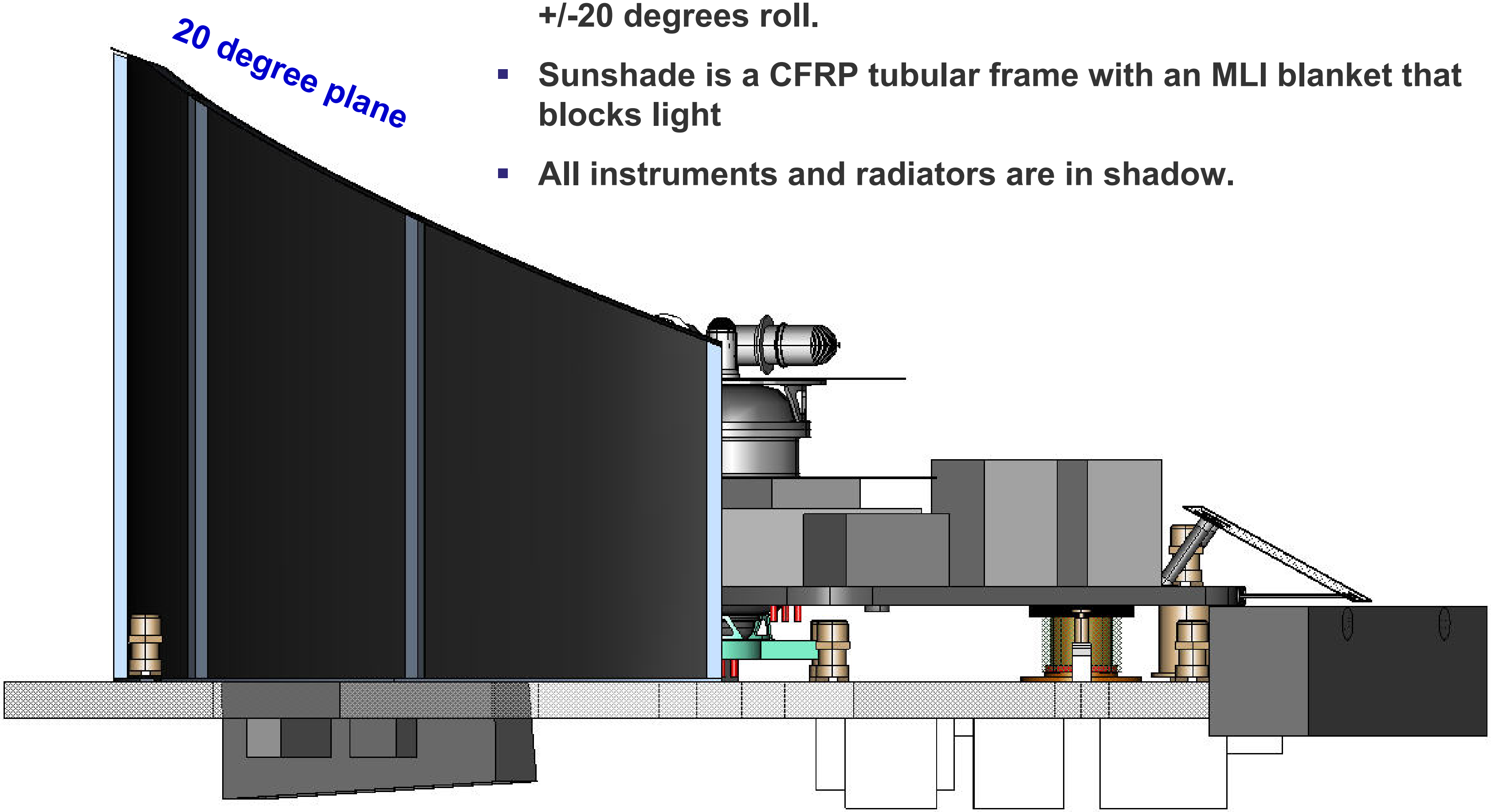
- XPOL, XMS, WFI/HXI, & HTRS are on the Moving Instrument Platform which rotates ± 70 degrees to position each instrument at the focus
- All instrument-related wire harness travels through a 15cm hole in the rotational stage and twists along with the platform.
- XMS, WFI/HXI, and XGS shall have Focus Mechanisms, the XGS-OP Camera also requires a translation stage in the cross-dispersion direction (+/-X)
  - Focus and Translation Stages are described in the Pointing / Alignment Section
- Launch Locks lock the MIP to the FIP during launch
  - The MIP Launch Lock also provides Launch Loads relief for the XMS Focus Actuators

IXO's Rotation Stage

- **Stage consists of a large gear which is driven by two redundant electric motors.**
  - **Stepper motors with encoders.**
  - **Motors have a clutch for engagement/disengagement.**
  - **Motors have the usual redundant windings and controllers, etc.**



Sunshade



- Observatory pointing requirements are +/-20 degree pitch and +/-20 degrees roll.
- Sunshade is a CFRP tubular frame with an MLI blanket that blocks light
- All instruments and radiators are in shadow.

Deployment Module

The deployment module consists of the following:

- **Three ADAM masts**
  - ATK (ex AEC-Able) commercial product consisting of a series of longerons, battens, and cross-braces folded inside a canister.
- **Deployable shroud**
  - Two concentric 9-sided MLI blankets stitched in an accordion shape
  - Attached to the shroud are two baffles (.001” Tantalum foil with polymer reinforcement membrane) with cutouts for the x-ray beams.
- **Shroud Stowage Ring**
  - 9-sided CFRP C-channel to hold the stowed shroud
- **Deck**
  - 9-sided 2” thick honeycomb panel onto which the 3 ADAM masts and shroud stowage ring are mounted.

Deployment System Requirements / Goals

- Approximately 12 meters deployment length.
- Must be able to deploy mass/inertia of IM, shroud, harness, and baffles. Therefore, the system must have significant deployment force.
- Must fit inside the Bus when stowed for launch.
- Deployed 1st bending and torsion modes > 1 Hz. Satisfies ACS Karman Filter algorithm. Could go lower if necessary.
- Deployment positioning capability goal is to put the focal point within a sphere of 2mm diameter true position.
  - Additional mechanisms on instruments provide the fine positioning.
- Deployed stability: Varies per degree of freedom. See requirements sheets.
  - Generally sub-millimeter.
- Deployment time: not important, < 4 hours
- Deployment power: within capability of IXO's EPS.

Deployment Method Trade Study

- Several deployment methods were studied including:
  - Multiple (Able Deployable Articulated Mast) ADAM masts from ATK (previously known as AEC-Able) .
  - A single "octoADAM" mast of 4 m diameter which surrounds the FMA.
  - A single thin walled boom (3.4 m diameter, 10 m long) which could be deployed by several methods
  - Multiple small diameter telescoping Booms
  - Multiple Coilable Booms
  - Multiple Bi-Stem actuators
- We concluded that the ADAM mast combined the best stiffness-to-weight, positioning precision, and highest packaging density with flight heritage of any option.
- As a further bonus, an upcoming high-energy X-ray mission called Nustar is also using a single ADAM mast for a 10 m deployment.

ADAM Mast Flight Heritage

Applications			
Program	**Customer**	**Technology**	**Application**
IPEX II	JPL	ADAM	Micron-level stability flight experiment
SRTM	JPL	ADAM	SAR antenna deployment
Wide Swath Ocean Altimeter	JPL	ADAM and ESS	Deployable SAR, Fixed-Baseline Interferometer
AstroPhysics Programs	Various	ADAM	Occulter Deployment, instrument and detector separation
NuStar	JPL	ADAM	Deployable X-ray optical bench

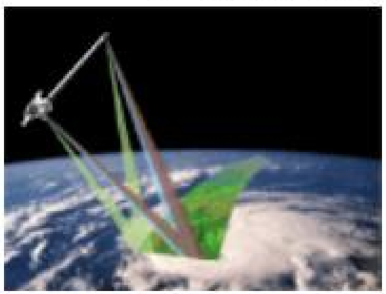
- **International Space Station FAST masts**
  - **35m long, metallic version of ADAM mast. Six currently flying on ISS.**
- **SRTM used a 60m ADAM mast with high deployment accuracy and stability.**
- **Nustar will use an ADAM mast in 2011.**
  - **10 meter deployment length. Mast diameter and components are about 55% size of IXO's ADAM mast. Similar positioning requirements.**
  - **Mast deploys harness approximately equal to its mass. Harness is routed through the mast.**

ADAM Mast on SRTM

Shuttle Radar Topography Mission (SRTM)

SRTM mapped 80% of the Earth's land mass in a single 11-day Shuttle Flight - February 2000

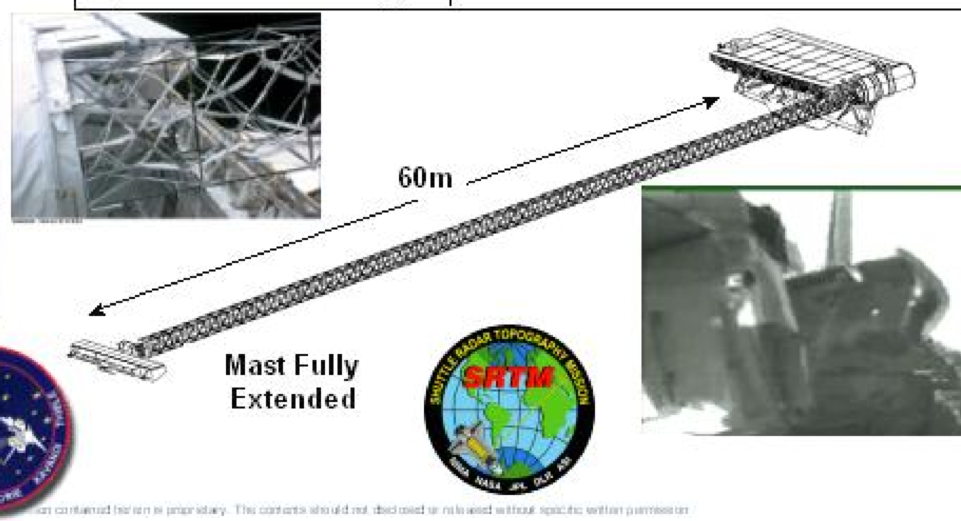
- Deployed/retracted 400-kg antenna 60-m from the Shuttle Cargo Bay
  - Including ~200-kg of electrical harnesses, coaxial & fiber optic cables along the length of the mast
  - Validated extreme stability and precision of ADAM technology



Measured Deployment Accuracy (Repeatability @ 60m)

Length	<± 1.3 mm (from +66C to -60C)
Tip Translation in Shear	< ± 0.25 mm
Tip Twist in Torsion	< ± 0.02°
Tip Rotation in Bending	<<± 0.005°

!

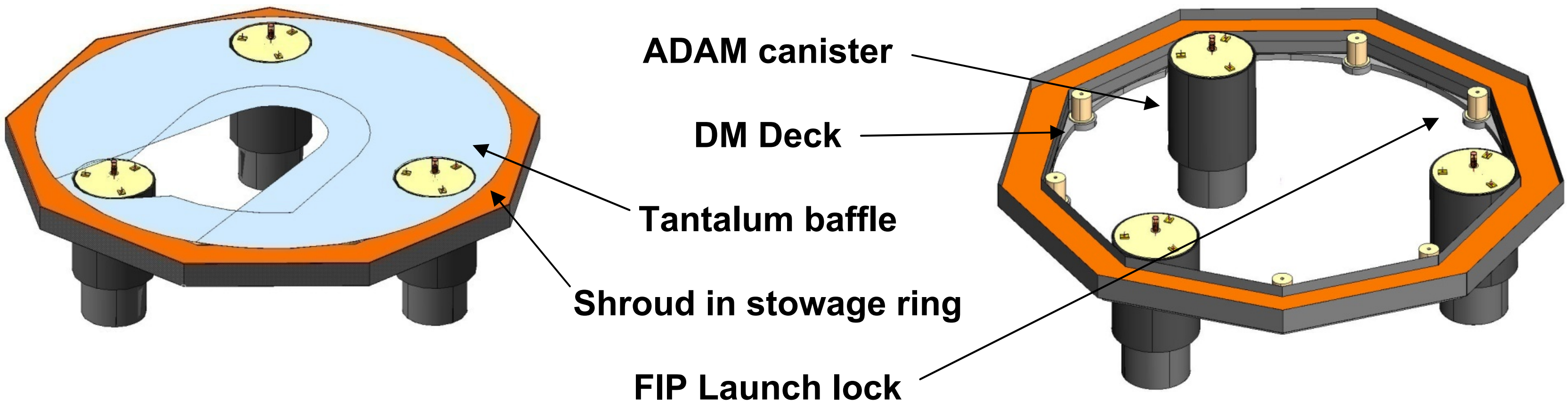


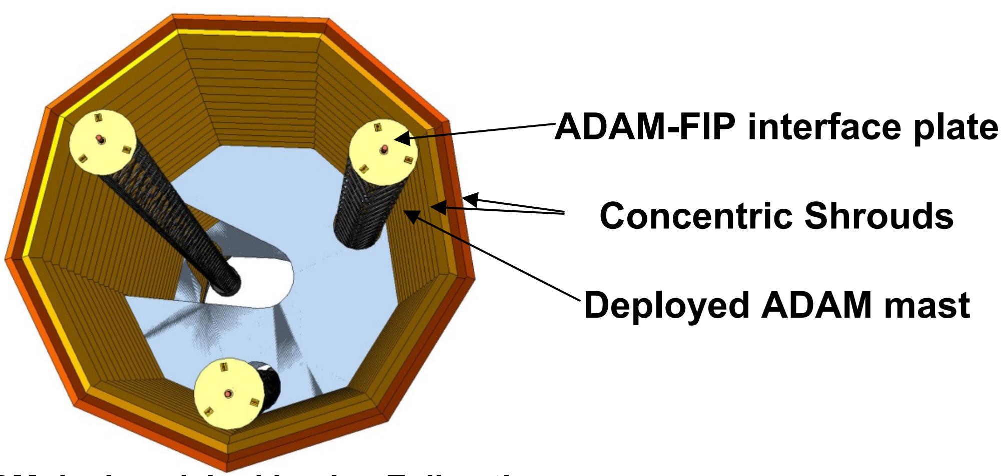
ATK ABLE

14

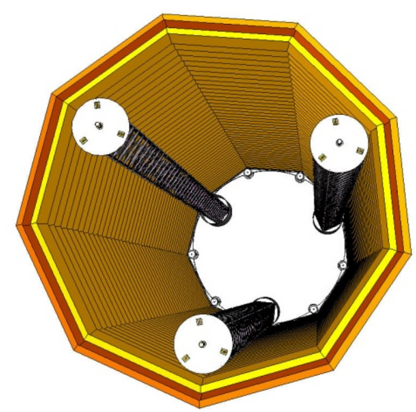
Deployment Module Implementation

- 3 ADAM masts deploy the IM a distance of 11.9 meters.
- Masts stow into canisters 65 cm diameter, 1 m long. **Canisters are located on a circle 2.87 m diameter.**
- Harness, shroud, and baffles are pulled up by the ADAM masts.



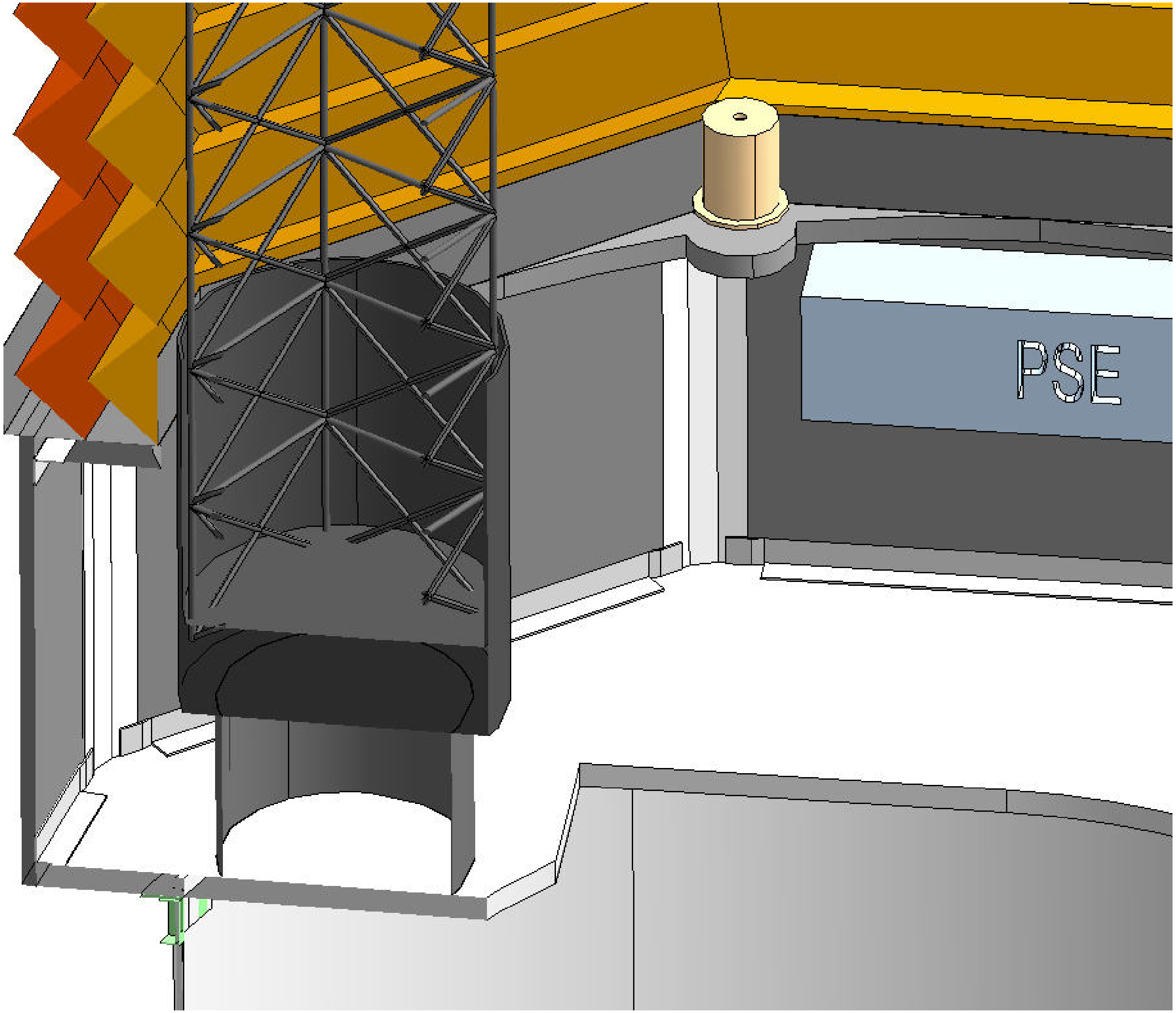


DM deployed, looking in +Z direction



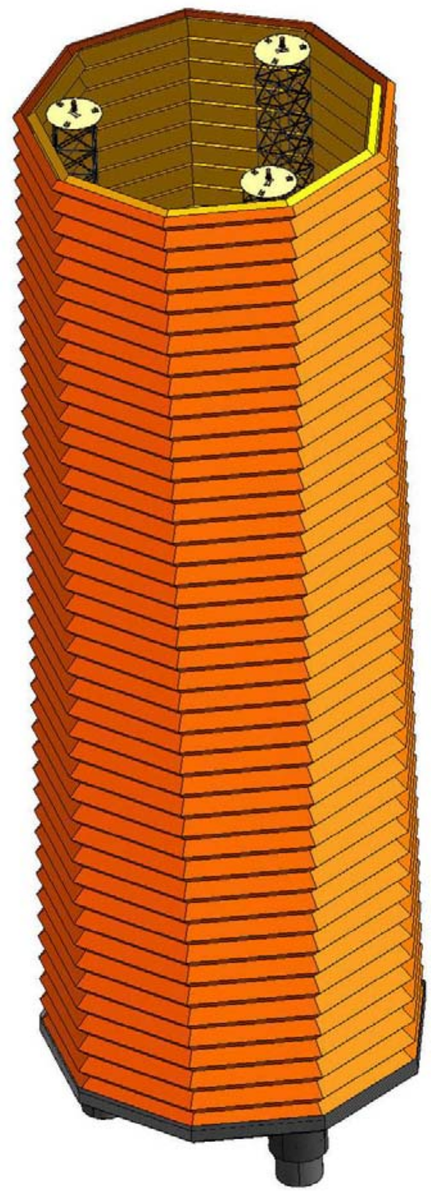
DM deployed, baffles removed for clarity

Interface between Deployment and Spacecraft Modules

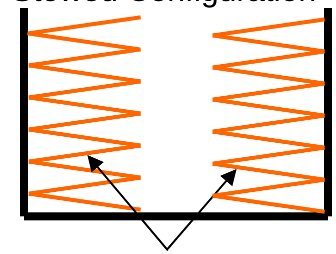


Shroud Subsystem

- **Shroud is necessary to block light from entering instrument apertures.**
- **Shroud assembly consists of two MLI blankets which are pleated like an accordion or camera bellows.**
- **Pleats allow the shroud to be folded up into a channel located on top of the spacecraft bus for stowage**
- **Two concentric blankets separated by 10 cm form a “Whipple shield” which reduce micrometeorite penetrations from thousands to ~35.**
- **MLI is 5 layers of   -mil aluminized Mylar and Dacron scrim cloth with 2-mil Kapton inner and outer layers. Innermost layer is black.**

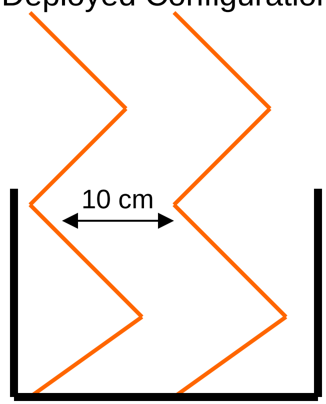


Stowed Configuration



Concentric MLI blankets
In Stowage Channel

Deployed Configuration



Shroud Prototypes

- To verify the deployable shroud TRL, the GSFC Blanket shop created a 1/25th scale prototype, and a full scale section.
- Scale shroud stows to 3.5 cm with some compression force and extends to 49 cm nominally.
- Full-scale 4-pleat section shows that the shroud can stow in < 20 cm height.

49 cm
65 cm max

14.5 cm ID
18 cm OD

Flight Example: Hubble's ESM Accordion Blanket

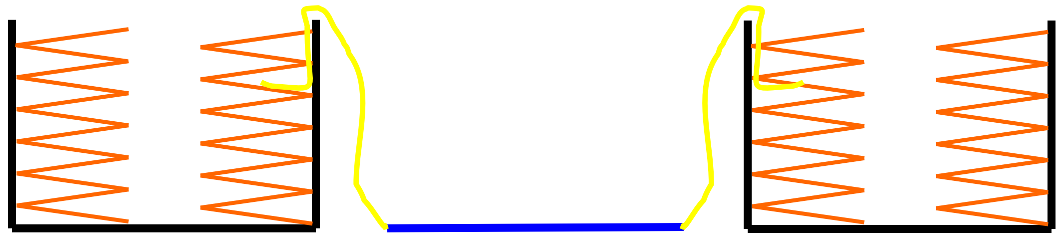
- Accordion-style blanket made for HST Electronic Support Module (ESM) on STS-109 (March 2002). This blanket protected the ESM in the shuttle bay and was deployed & retracted by an EVA astronaut.
- 5" tall when compressed, expands to 42" tall. Fully stretched length of MLI is 68"
- Approximate size is 42"x36"x3"

Baffle Interface to Shroud

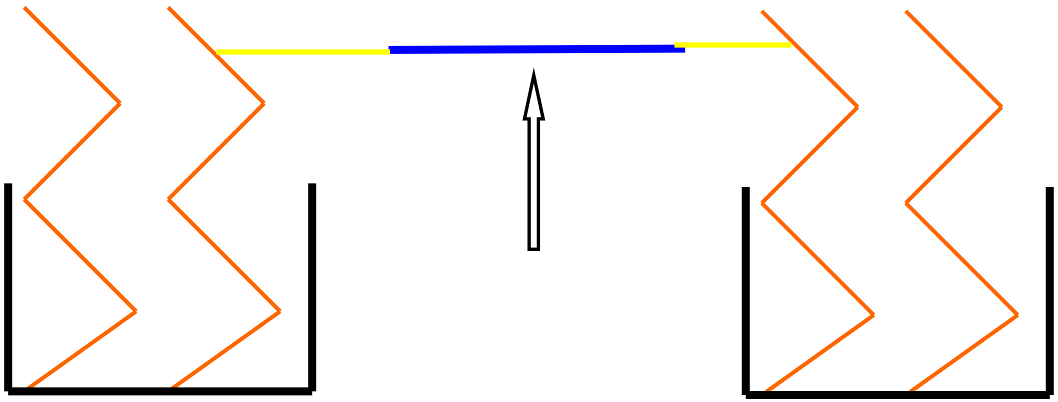
Baffles deploy with the shroud

- Attached via thin wires or Kevlar strings to the appropriate pleat of the shroud

- **No direct interface to the masts**



Stowed configuration



Deployed configuration

Accommodating Harness in the Masts

- There will be harness between the instrument module and the spacecraft module. Redundant services A & B.
- Wire harness will thread through the masts similar to the SRTM and Nustar missions.
  - SRTM's harness weighed 500 kg. Nustar's harness weighs same as the ADAM mast.

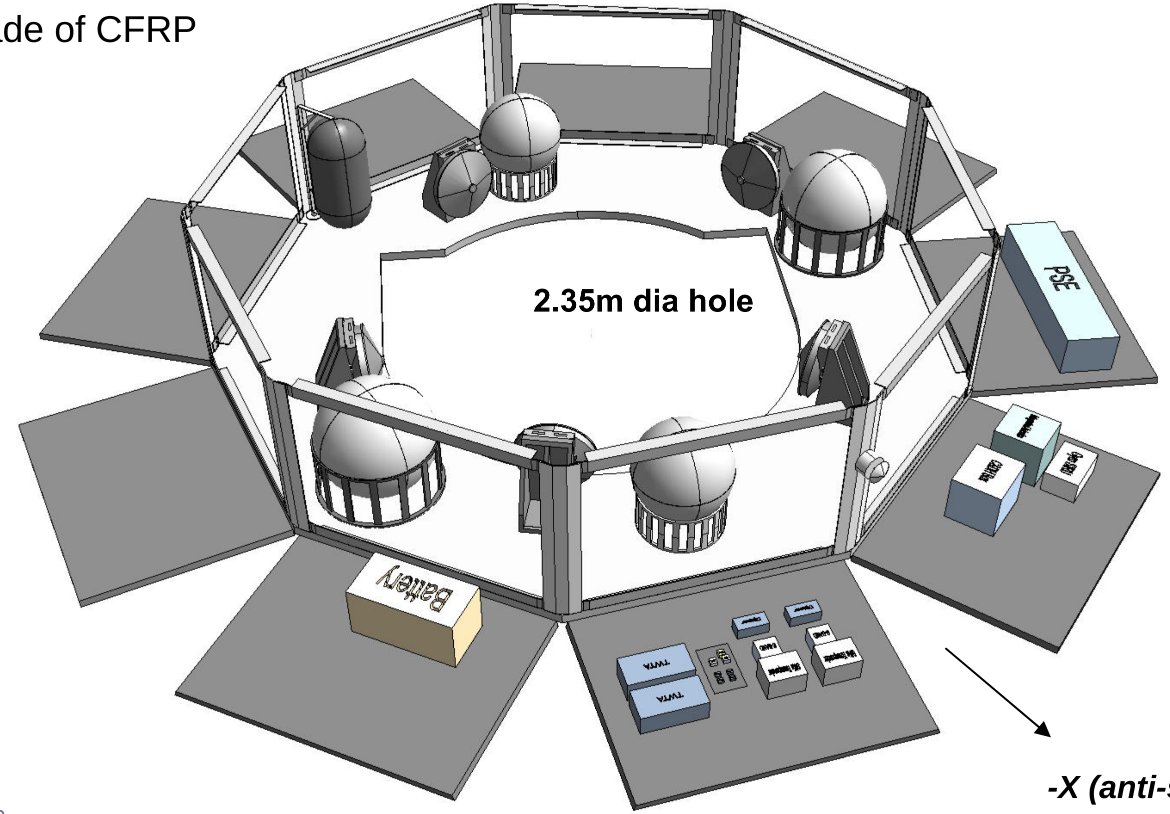
Spacecraft Module

The Spacecraft Module (SM) consists of the following:

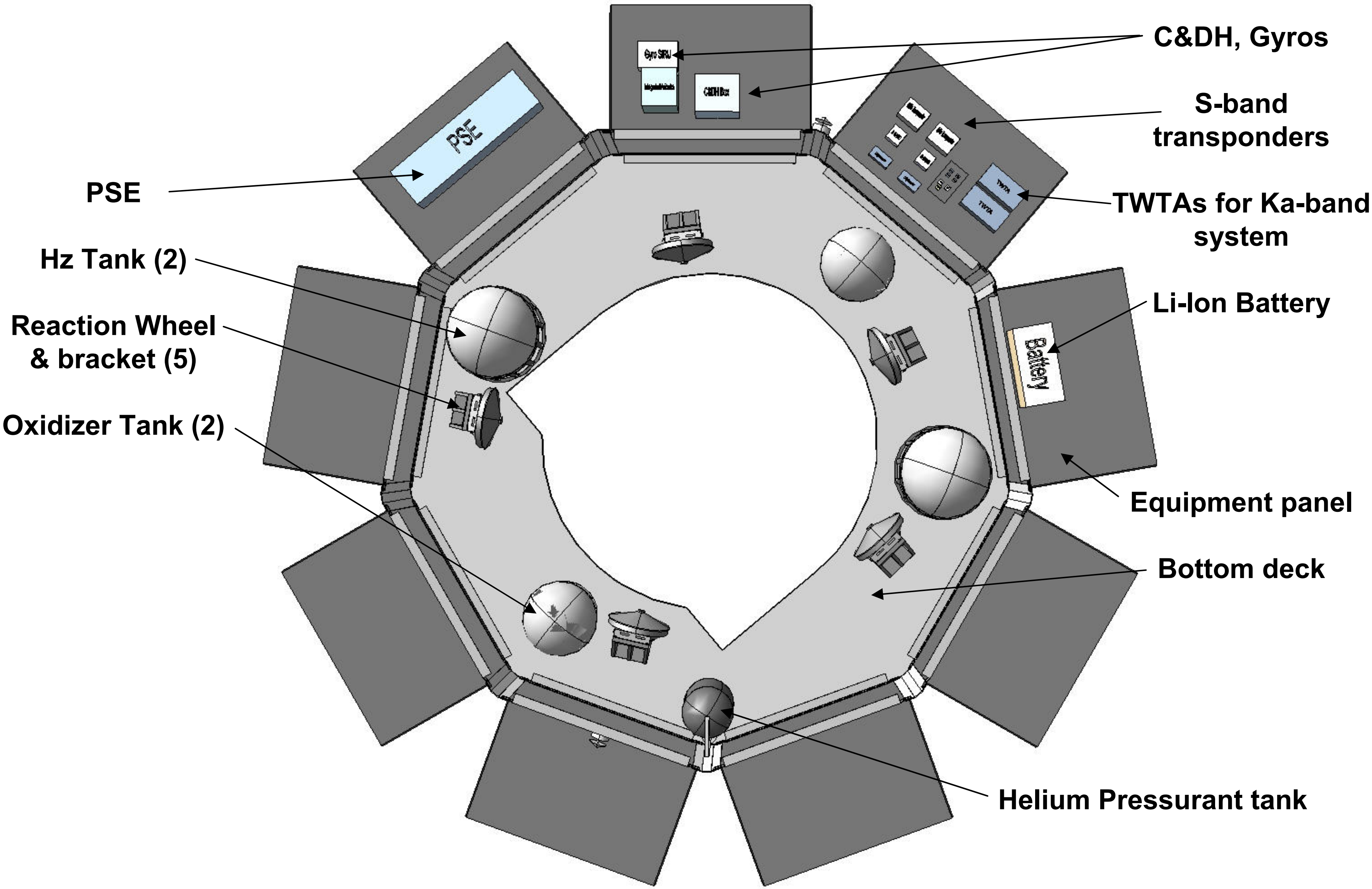
- Spacecraft Bus (SB)
  - 9-sided volume with honeycomb panels and CFRP framework
- Fixed Metering Structure (FMS)
  - Advanced Grid Stiffened CFRP cylinder
- Avionics
  - PSE, Battery, C&DH, transponders, Reaction wheels, gyros, etc.
- Harness
- Propulsion system
  - Bi-prop system with 2 fuel, 2 oxidizer tanks, 1 He Pressurant tank
  - Four thruster triads
  - Four 0.9 N solar pressure torque offload trim thrusters (primary and backup)
- Solar Arrays
  - One 13.5 m^2 fixed array on FMS, two 3.8 m diameter deployable Ultraflex solar arrays
- Antennas
  - 1 Ka-band 0.7 m diameter antenna on azimuth & elevation gimbals
  - 2 S-band Omni antennas

Bus Module Description

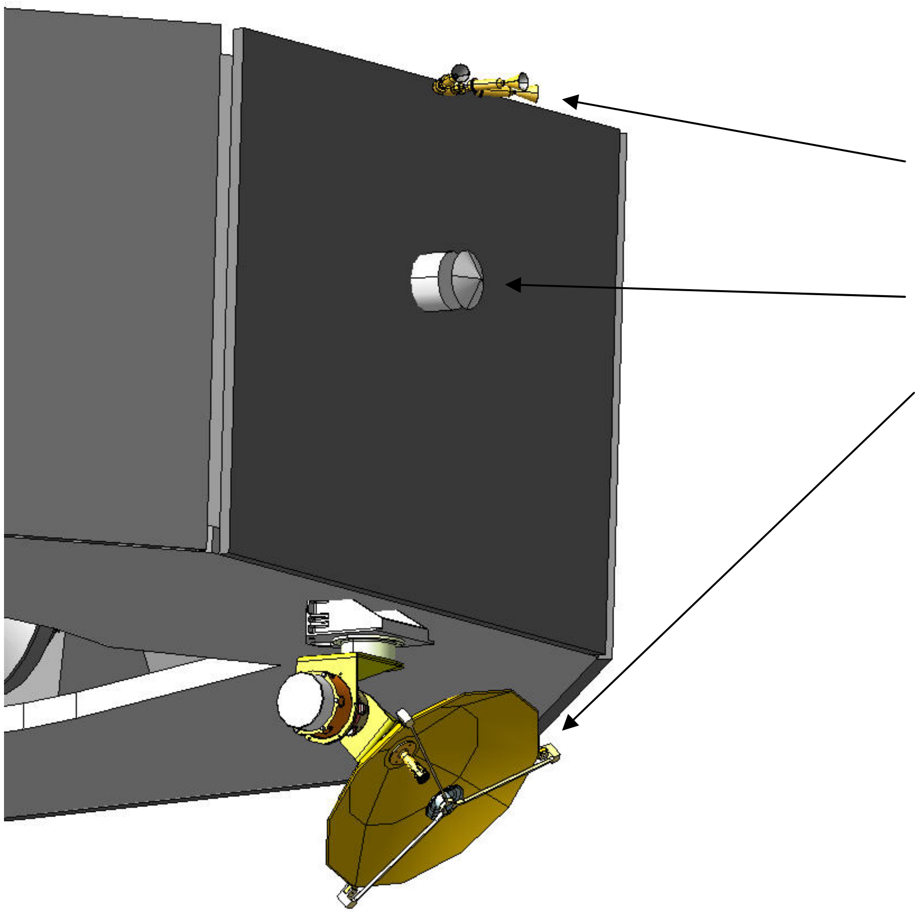
- Bus is 9-sided to allow symmetric placement of 3 ADAM mast canisters.
- Avionics are mounted to the 4 anti-sun panels so they may radiate heat to deep space.
- Propulsion tanks oriented symmetrically around centerline to miminize drift of CG as propellant is consumed.
- 2.35 m diameter hole in bottom deck is for the FMA X-ray cone and XGS grating x-ray beams.
- Equipment panels made of CFRP honeycomb panels (graphite facesheets, 5052 aluminum core).
- Bottom deck has aluminum facesheets and embedded CCHPs to reduce thermal gradients.
- Frame made of CFRP



Bus Layout


C&DH, Gyros
S-band transponders
TWTAs for Ka-band system
Li-Ion Battery
Equipment panel
Bottom deck
Helium Pressurant tank
PSE
Hz Tank (2)
Reaction Wheel & bracket (5)
Oxidizer Tank (2)
PSE
Gyro SIRU
C&DH Box
Battery

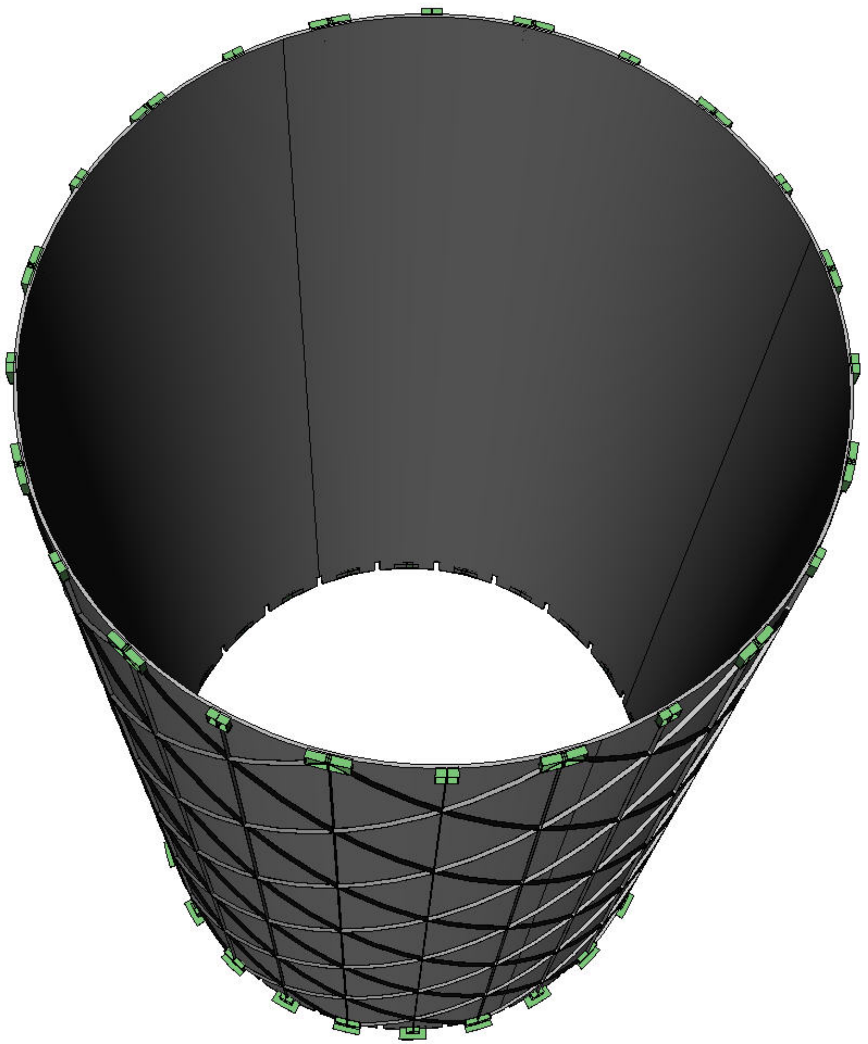
Antenna and Thruster Detail



- Thruster Triad is located at highest point on Bus panel
- Omni antenna on the +X and –X sides
- Ka-band antenna has an azimuth and elevation gimbal. 0.7 m antenna

Fixed Metering Structure (FMS)

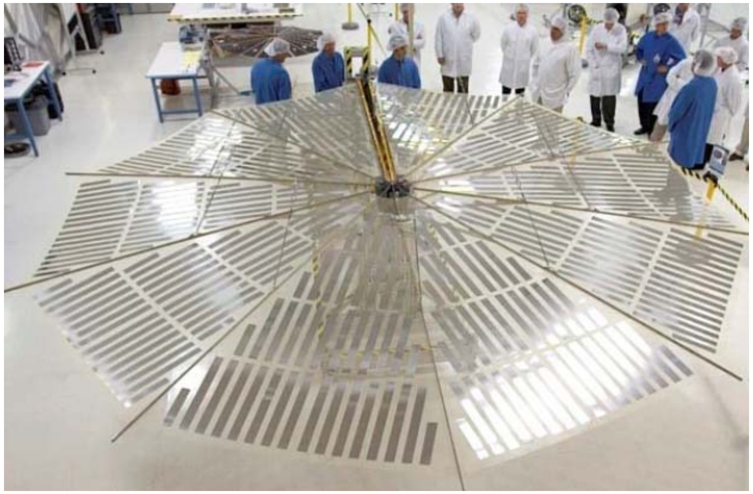
- FMS provides 6.7 m spacing from the FMA, support structure for the solar arrays and thrusters.
- CFRP cylinder consisting of a thin skin (1.5 mm) with vertical longerons and spiral rib stiffeners 6 mm wide, 38 mm tall.
  - Advanced Grid Stiffened geometry (isogrid)
- M55J/954-3 composite in quasi-isotropic near zero-CTE layup.
- Made in one piece via Automatic Fiber Placement Machine.
  - similar to Boeing 787 Dreamliner fuselage
- Titanium end fittings are bonded to top and bottom perimeter.



Ultraflex Array Heritage and Deployment Video

ST-8 Project
ETU Ultraflex Array

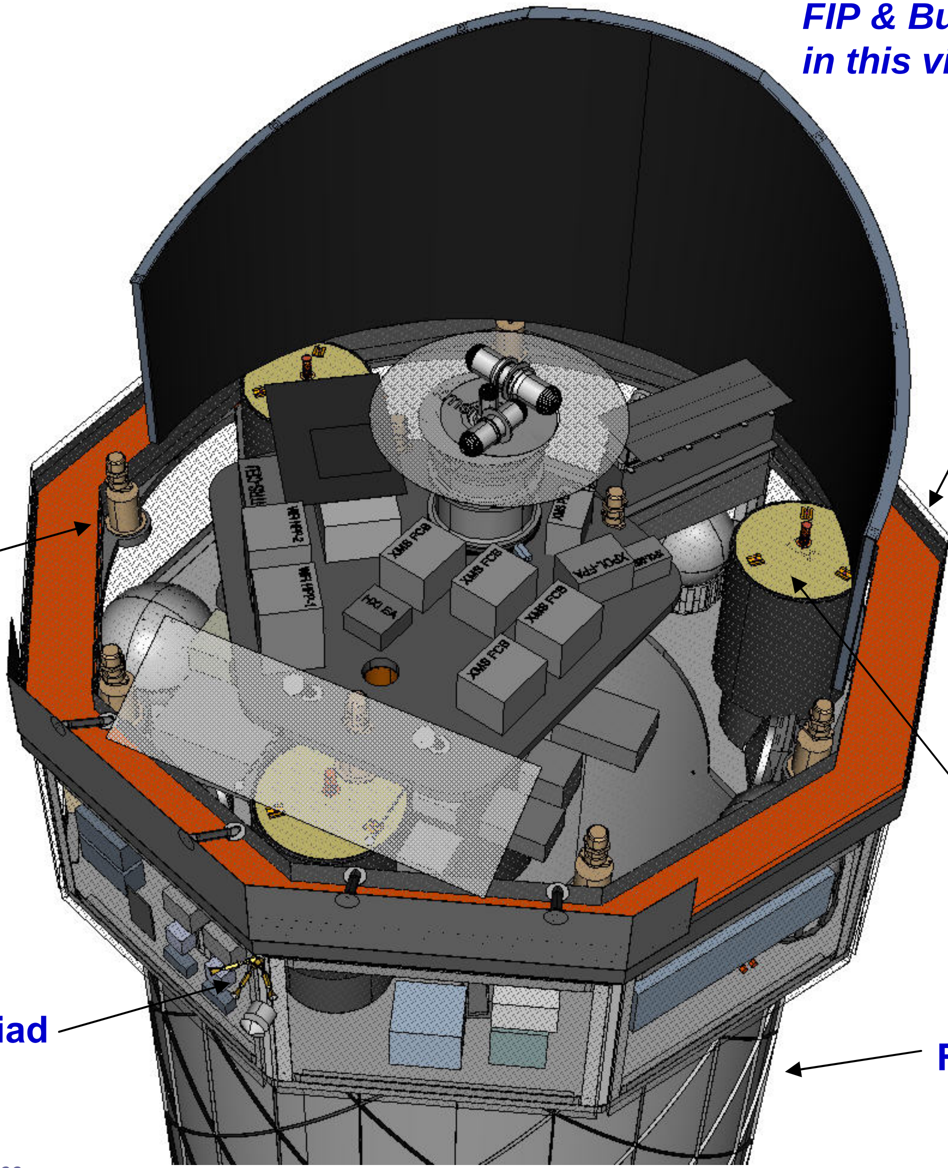
Mars Phoenix Lander
Ultraflex Array



Orion Project
ETU Ultraflex Array
(5.5 m dia)

Stowed IM, DM, and SM

FIP & Bus Panels are semi-transparent in this view



~4 m diameter Shroud Stowage Channel contains the shroud

Launch locks secure the Instrument module to the Bus for launch

Baffles are not shown in this view but reside under the FIP and are connected to the shroud

ADAM mast interface to the FIP

22N thruster triad

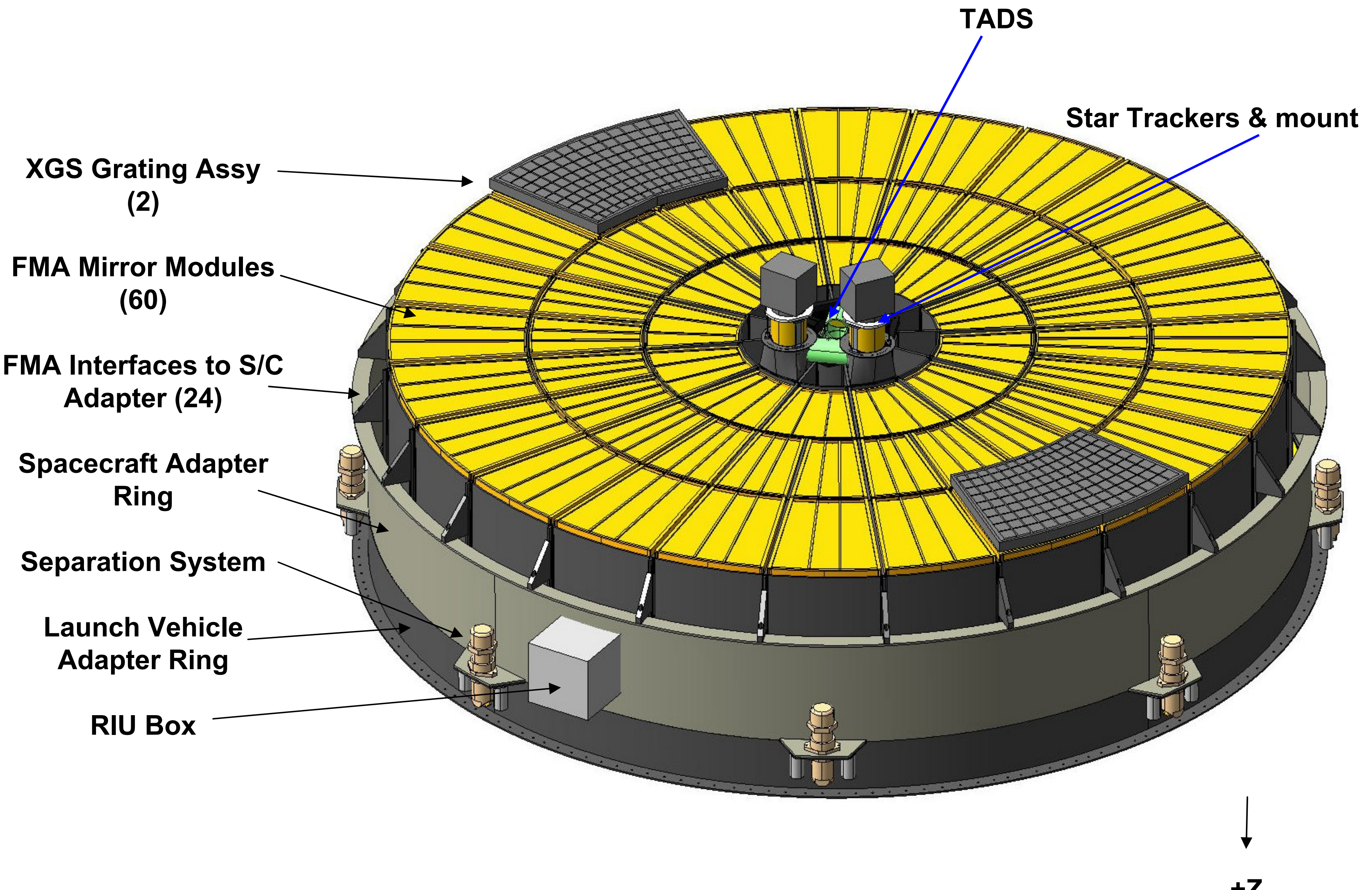
Fixed Metering Structure

Optics Module (OM)

The OM consists of the following:

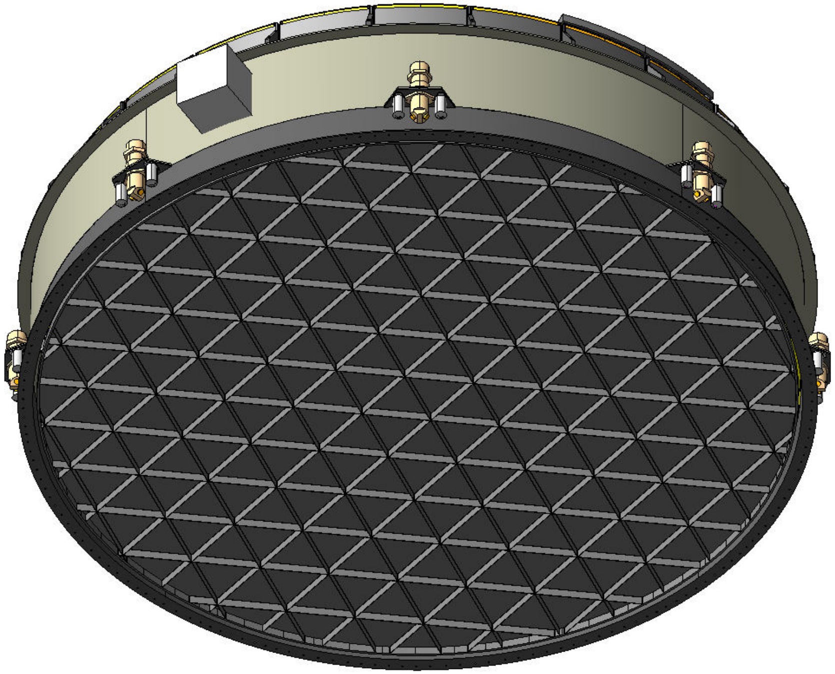
- Flight Mirror Assembly (FMA)
  - ~1750 kg glass & CFRP assembly, 3.3 m diameter, 80 cm tall
  - HXMM installed in center of FMA
- X-ray Grating Assemblies (2) covering 2 outer mirror modules each
- Telescope Alignment and Detection System (TADS)
  - Mounted to inner hole of HXMM. Provides knowledge of focal plane – to – FMA position for x-ray image reconstruction.
- 2 Star Trackers
  - LMMS AST-301 trackers mounted to inner ring of FMA and interface to the TADS.
- Spacecraft Adapter Ring
  - 3.4 m diameter 7075 aluminum ring with CCHPs bonded to inside wall minimize thermal gradients
- Launch Vehicle Adapter Ring and Separation System
  - 3.4 m diameter 7075 aluminum ring with 8 pyro-activated separation nuts and springs to separate IXO from the launch vehicle truss adapter
- Deployable Sunshade
  - 1.8 m tall, 3.4 m diameter. Inflatable or pop-up deployment
- RIU Electronics Box
  - Heater controller cards, power distribution
- External FMA Cover
  - CFRP isogrid cover jettisoned with springs and low-shock release system.
- Internal FMA Cover
  - Deployable with zero X-ray obstruction

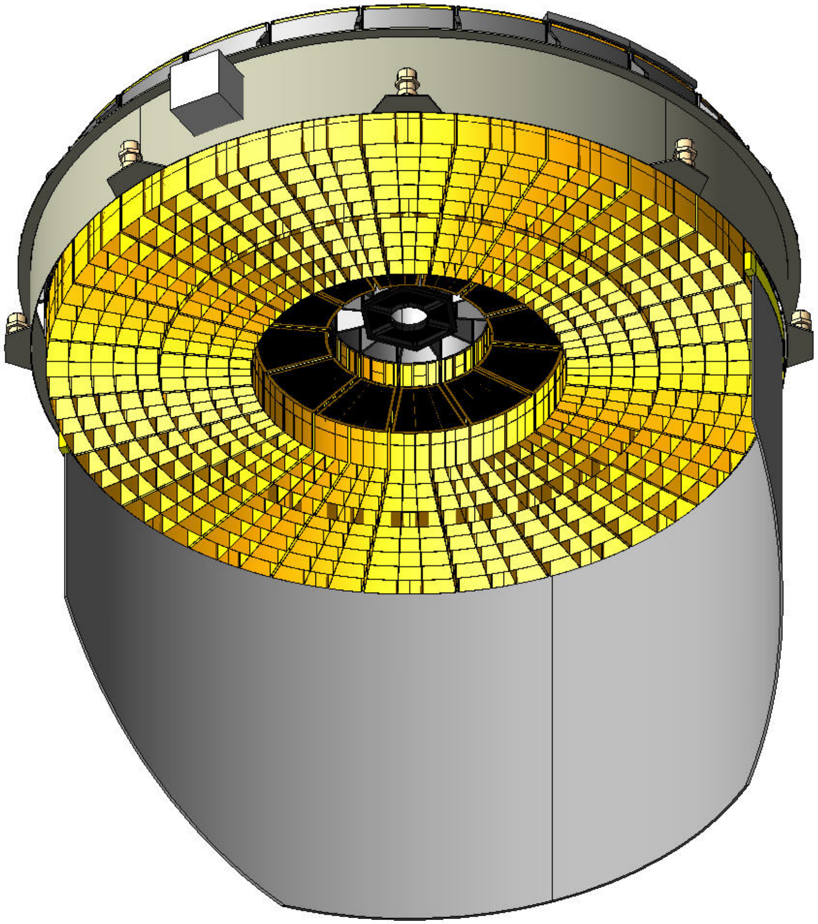
Optics Module Aft End



Optics Module Fore End

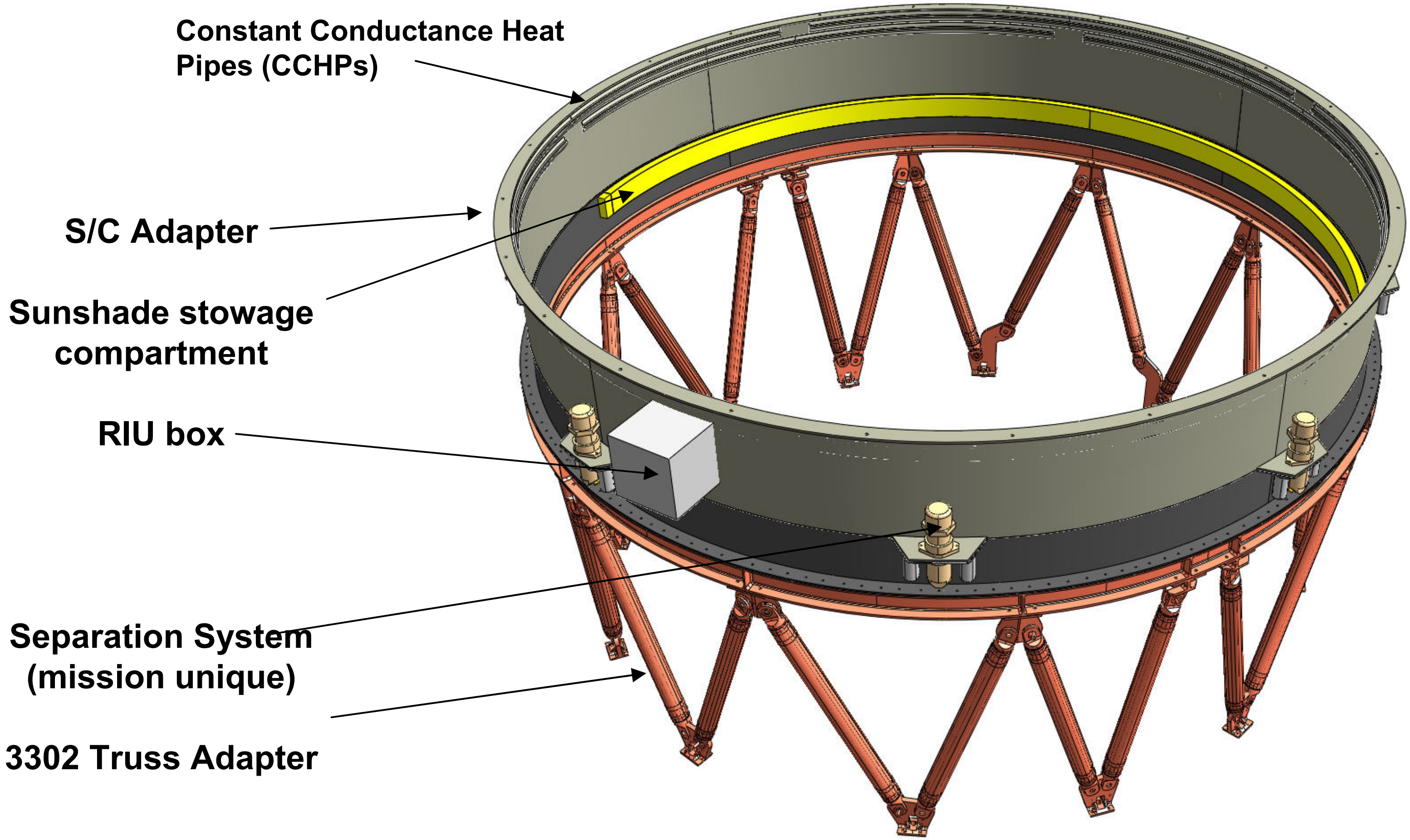
- Isogrid cover is jettisoned after launch
- Sunshield is deployable.
  - Inflatable system proposed by L'Garde Inc. weighs ~2.8 kg.





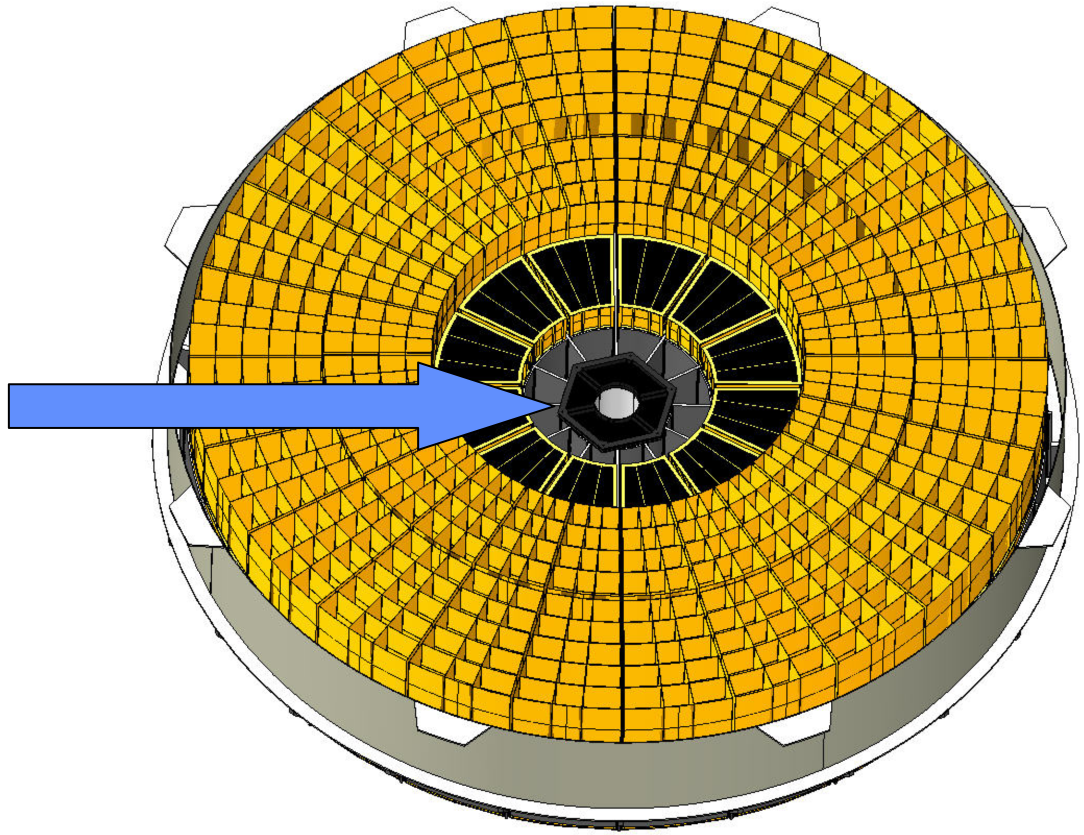
OM Interfaces to Launch Vehicle

- Launch Vehicle Adapter (LVA) bolts to 3302 Truss Adapter
- LVA attached to Spacecraft Adapter via 8 sep-nuts
  - ” bolt NSI-actuated Sep-nut release system with push-off springs

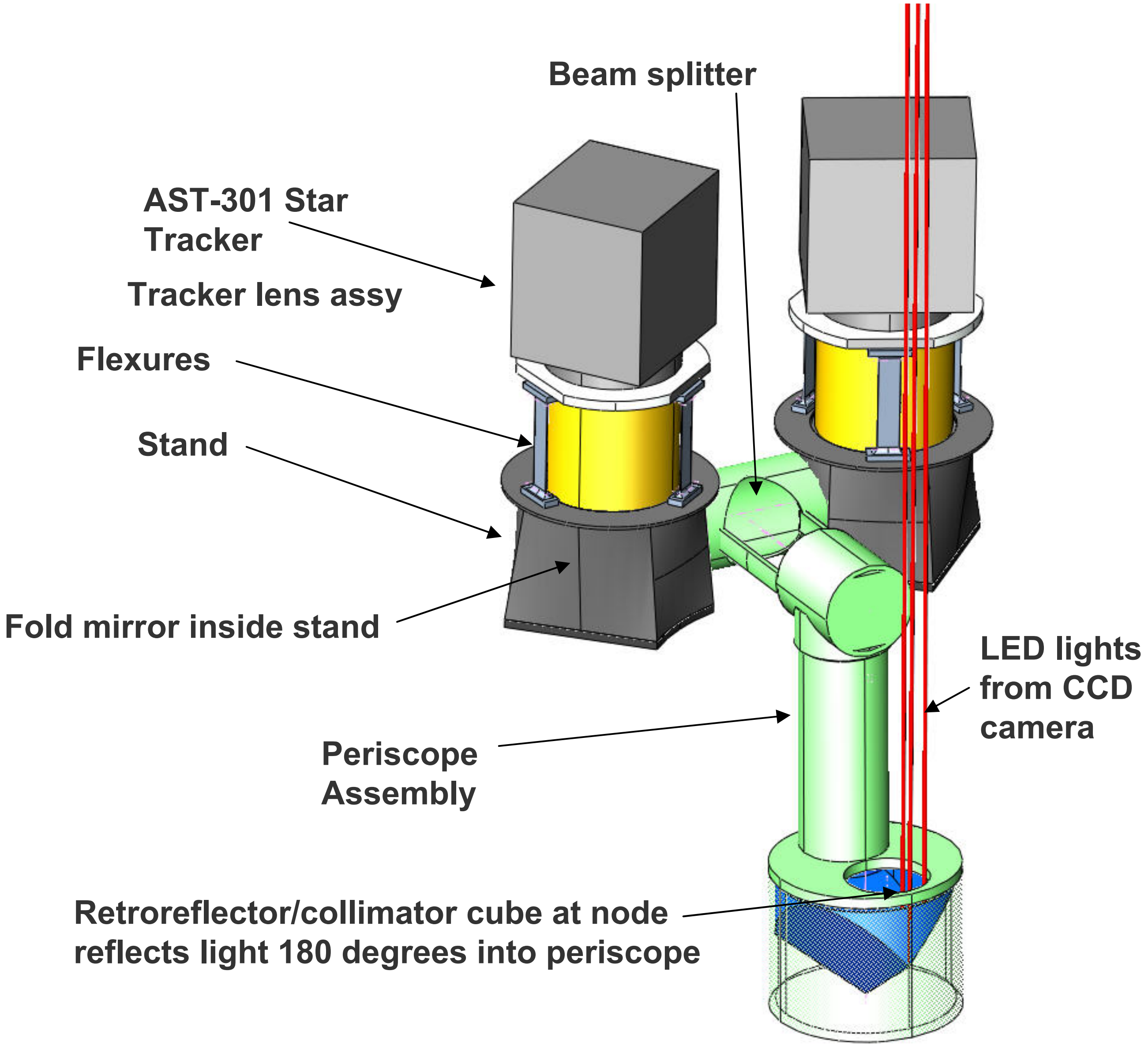


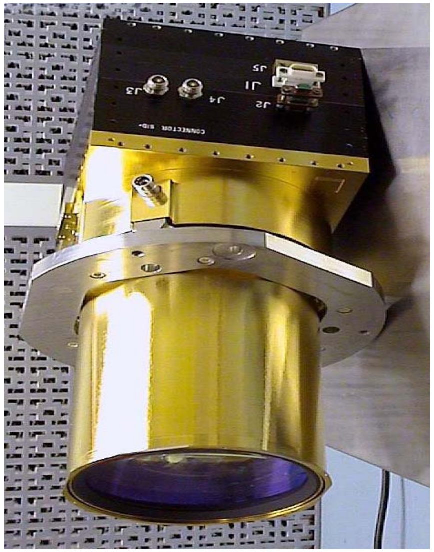
Hard X-ray Mirror Module (HXMM)

- HXMM will be similar to Suzaku, Astro-H and Nustar designs.
  - 18 cm inner diameter, 42 cm outer diameter, 40 cm long.
- Will be installed into center hole of FMA via flexures.
- TADS corner cube fits into the HXMM



Telescope Alignment and Detection System

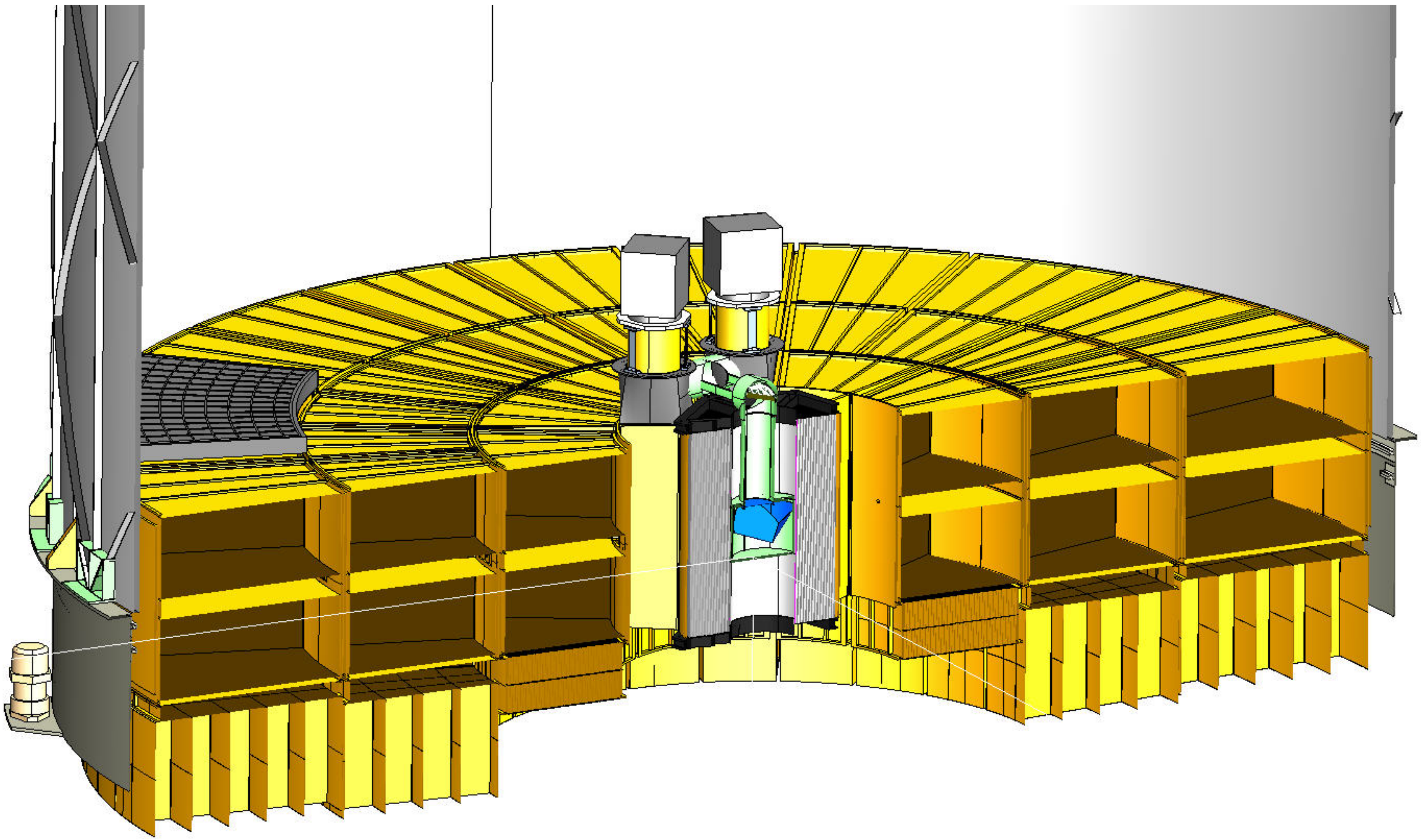




AST-301 Tracker

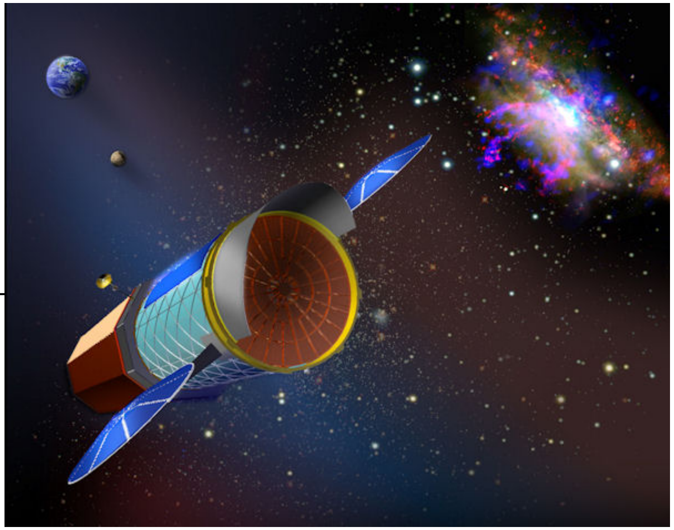
FID Light (LED light) assembly, 45 mm long

OM and SM Interfaces



IXO Systems Definition Document
Chapter 4

Integrated Modeling

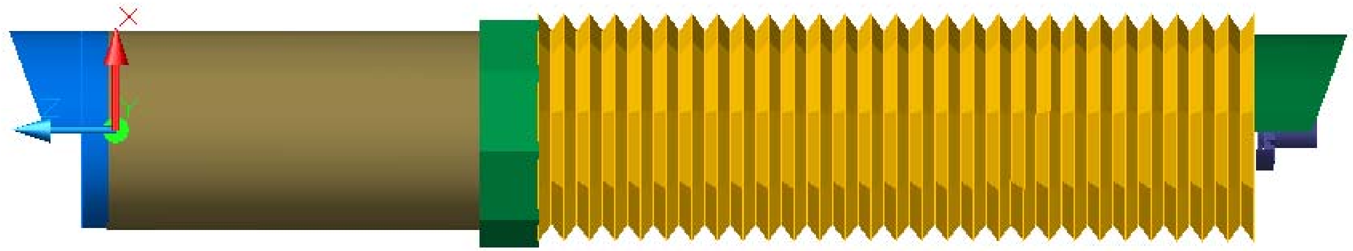


Modeling Applications

- Observatory 3-D Thermal Model was used for:
  - Observatory thermal design, heater and radiator sizing, component placement, materials selection
  - Thermal Analysis in support of Integrated Thermal Distortion Analysis
  - FMA Thermal Interface Modeling in support of FMA Temperature Control design
- FMA Thermal Modeling was used for:
  - Defining thermal Interface between the FMA and the Observatory
- Observatory Finite Element Model was used for:
  - Modal Analysis
  - Jitter Analysis
- Integrated Models were used for:
  - Integrated Thruster Firing Disturbance Analysis
  - Integrated Thermal Distortion Analysis: Thermal + FEM

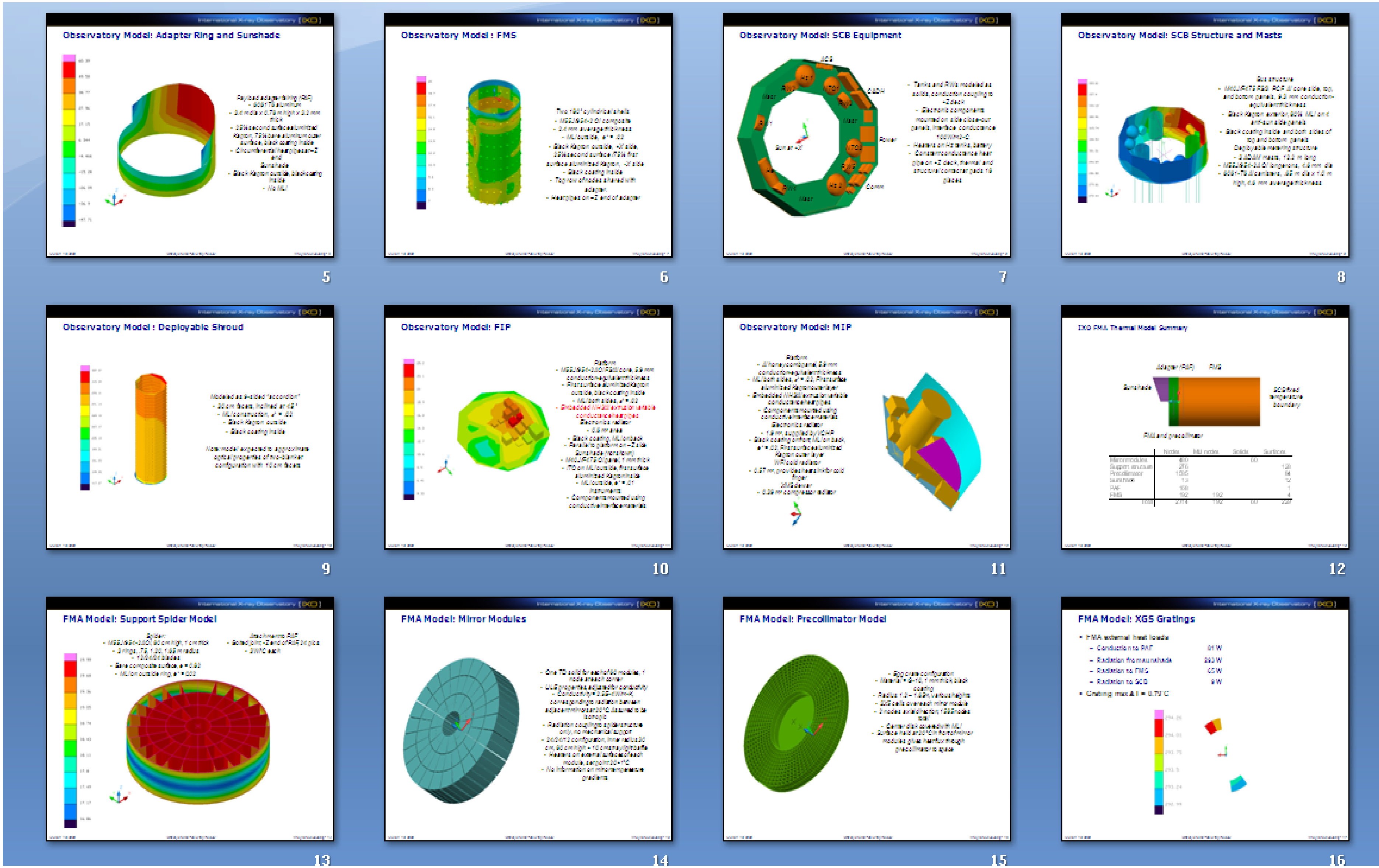
Observatory 3-D Thermal Model

IXO Observatory 3-D Thermal Model



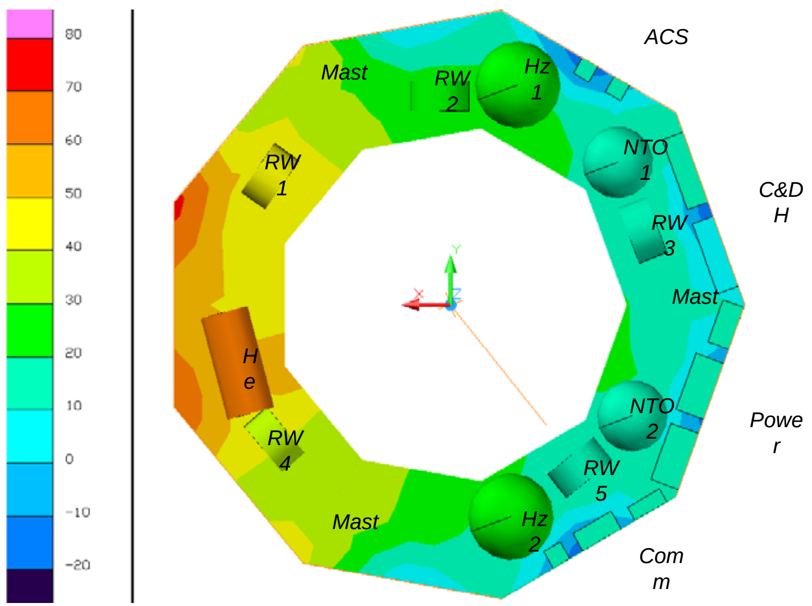
	Nodes	MLI Nodes	Solids	Surfaces
FMA	29	18	1	2
FMS	162	162		2
FIP	40	44	5	12
MIP	68	103	14	3
Masts	531			15
PAF	52			3
SCB	46		6	15
Shroud	525	525		505
Total	1453	852	26	557

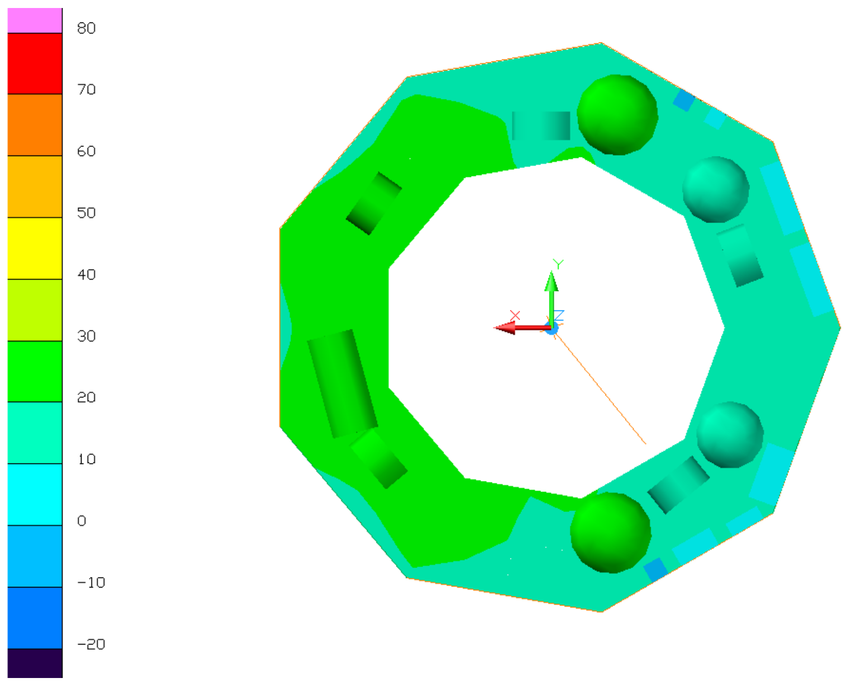
Thermal Model Details



Observatory Thermal Design Analysis

Thermal Design Optimization - Bus Component Temperatures
w / Radiation / Conduction Only vs. w / Circumferential Heat Pipes





Thermal Design - Bus Component Temperatures

Component	Temperature (°C)			Heater Power (W)
	Predicted Downlink	Allowable (1)		
		Min	Max	
DSN S/Ka-Band transmitter 2	18.8	-10	40	
DSN S/Ka-Band transmitter 1	5.1	-10	40	
10 Watt TWTA 1	17.8	-10	40	
10 Watt TWTA 2	0.9	-10	40	
S-band 5 watt power amplifier 1	-1.8	-10	40	
S-band 5 watt power amplifier 2	24.6	-10	40	
C&DH	6.6	-10	40	
C&DH	9.9	-10	40	
Hz Tank 1	28.3	20	30	20
Hz Tank 2	27.4	20	30	20
NTO Tank 1	15.1	0	30	
NTO Tank 2	15.4	0	30	
COPV He Tank PSI 80412-1	26.7	-10	40	
Power system electronics 1	5.1	-10	40	
Power system electronics 2	12.4	-10	40	
50 AH Li-Ion Battery	10.4	25	25	30
Star Tracker Processing Unit 1	13.3	-10	40	
Star Tracker Processing Unit 2	-1.1	-10	40	
Gyro 1	17.7	-10	40	
Gyro 2	1.2	-10	40	
Reaction Wheel 1	29.0	-10	40	
Reaction Wheel 2	19.3	-10	40	
Reaction Wheel 3	15.5	-10	40	
Reaction Wheel 4	25.0	-10	40	
Reaction Wheel 5	15.9	-10	40	

(1) With 10°C margin on operating temperature range

Some Component Allowable Temperatures based on typical values

Thermal Design - Payload Component Temperatures

	Component	Status	Predicted	Allowable	
				Min	Max
XMS	Cryocooler Compressor	On	30.2	10	40
	Pre-Amplifier/BiasBox (PBB)	On	4.2	-20	50
	Feedback/Controller Box (FCB) -1	On	4.6	-20	50
	Feedback/Controller Box (FCB) -2	On	5.0	-20	50
	Feedback/Controller Box (FCB) -3	On	5.6	-20	50
	Feedback/Controller Box (FCB) -4	On	5.7	-20	50
	Pulse Processing Electronics (PPE)	On	13.2	-20	50
	ADR Controller (ADRC)	On	4.5	0	30
	Cryocooler Control Electronics (CCE)	On	13.6	0	40
	Filter Wheel Control Electronics (FWC)	On	6.2	0	40
	Power Distribution Unit (PDU) -1	On	8.1	0	40
	Power Distribution Unit (PDU) -2	On	8.8	0	40
WFI	Focal Plane Assembly (FPA)	On	2.5	0	40
	Cold finger	On	-74.0	< -73	
	Hemisphere Pre-Processor-1 (WFI-HPP1)	On	10.7	0	40
	Hemisphere Pre-Processor-2 (WFI-HPP2)	On	11.0	0	40
	Brain/Frame Builder-1&2	On	4.1	0	40
	Power Conditioner-1 (WFI-PCU1)	On	10.5	0	40
	Power Conditioner-2 (WFI-PCU2)	Off		0	40

On/Off status for Mode 2 plus full XMS warm-up

Some Component Allowable Temperatures based on typical values

Thermal Design - Payload Component Temperatures (cont.)

	Component	Status	Predicted	Allowable	
				Min	Max
HXI	Sensor Head (HXI-S)	On	2.5	-22	-18
	Analog Electronic Unit (HXI EA)	On	3.1	0	40
	Digital Electronics (HXI DE)	On	7.3	0	40
	PSU (HXI PSU)	On	8.4	0	40
XGS	Grating Array-1	On	20.4	19	21
	Grating Array-2	On	19.9	19	21
	CCD Camera	On	-100.2	-110	-70
	Digital Processing Electronics (DPA)	On	6.3	-30	10
XPOL	Focal Plane Assembly (XPOL-FPA)	Off	1.4	-15	45
	Backend Electronics (XPOL-BBE)	Off	2.1	-15	60
	Control Electronics (XPOL-CE)	Off	6.1	-15	60
HTRS	Focal Plane Assembly (HTRS-DEU)	Off	2.3	-40	35
	Central Electronic Unit (HTRS-CEU)	Off	2.6	-40	35

On/Off status for Mode 2 plus full XMS warm-up

Some Component Allowable Temperatures based on typical values

Observatory Thermal Modeling Analysis Conclusions

- All Instruments and Avionics are within their Op range: Thermal requirements met
- Only conventional thermal control techniques are required

Observatory Thermal Components Mass Estimate

Thermal Design - Heat Pipe Mass Estimate

		Ea	No req'd	Total
Adapter	CCHP	5.6	3	16.7
SCB	CCHP	8.3	2	16.5
FIP	VCHP	3.4	2	6.9
MIP	VCHP	3.1	2	6.3
Subtotal		20.4		46.4
Contingency				30%
Total				60.3

Notes: Number required includes redundancy

SCB heat pipe weight includes mounting pads

Heat pipes are flight proven NH_3/Al extrusion design, 350 W-m capacity

Thermal Design - MLI Mass Estimate

	Area (m2)	Mass (kg)
Adapter	8.3	2.6
FMS	67.9	21.5
SCB	5.4	1.7
FIP panel	18.2	5.7
FIP elex radiator	0.7	0.2
MIP panel	3.8	1.2
MIP elex radiator	1.8	0.6
WFI cold radiator	0.5	0.1
Subtotal		33.7
Contingency		30%
Total		43.8

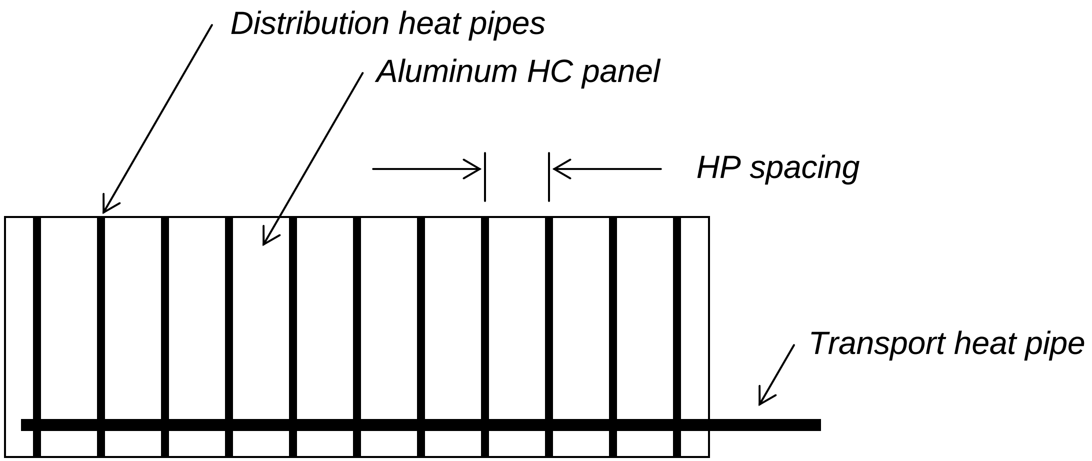
Notes: 20 layer blanket, .25 mil embossed Mylar inner layers
2 mil Kapton outer layers
Does not include deployable shroud

Thermal Design - IM Radiator Mass

- **Estimate based on Mode 2 + full XMS average power**
- **VCHP will accommodate lower power modes**
- **Estimate includes facesheets, core, adhesives, coatings, MLI on back, plus 25% for structure**
- **Temperatures and heat loads from observatory thermal model**

	Area (m^2)	Mass (kg)
MIP electronics	0.88	5.1
WFI cold finger	0.38	2.6
XMS compressor	0.71	4.2
FIP electronics	1.25	7.4
XGS camera	0.30	1.9
Total		21.2

Configuration of Radiator Panel with Distribution Heat Pipes



Distribution heat pipes:	*0.375 in. sq. with fins, 0.204 lb/ft*
Aluminum HC panel:	*20 mil facesheets, 3.1 pcf al core, 0.375 in thick*
Adhesives and coating 1 side:	*10 mils total, 0.05 lb/cu in*
MLI on back:	*0.32 kg/sq m*

This produces a 90% efficient radiator with a mass of just under 6 kg/sq m, including 25% for structure. The heat pipe spacing is ~25 cm. And it is nicely anisotropic, for VCHP reasons. Also, I don't think freezing of the distribution heat pipes should be a problem, since arrival of heat will eventually thaw things out.

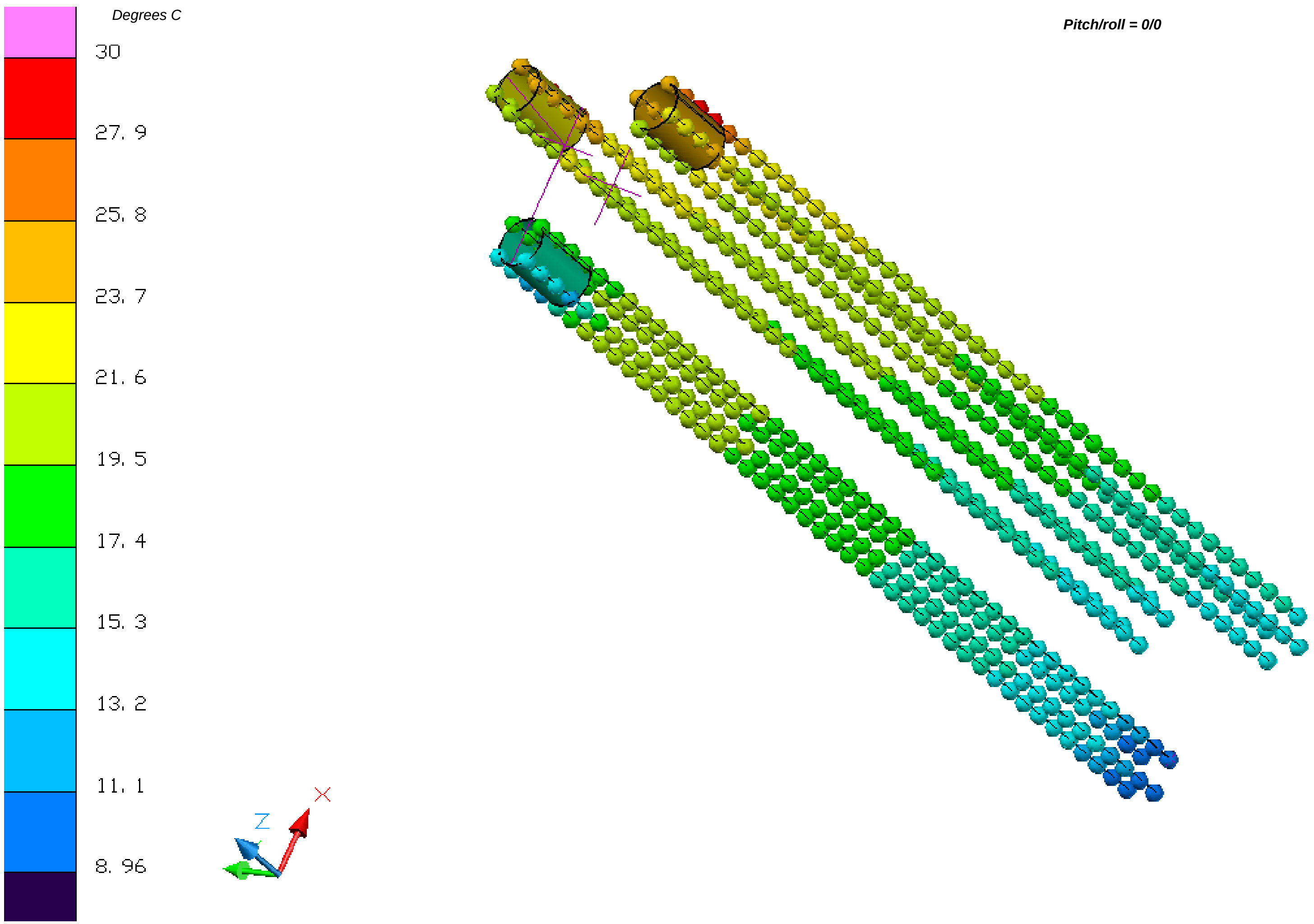
Thermal Distortion Analysis

in support of Integrated Thermal Distortion Analysis

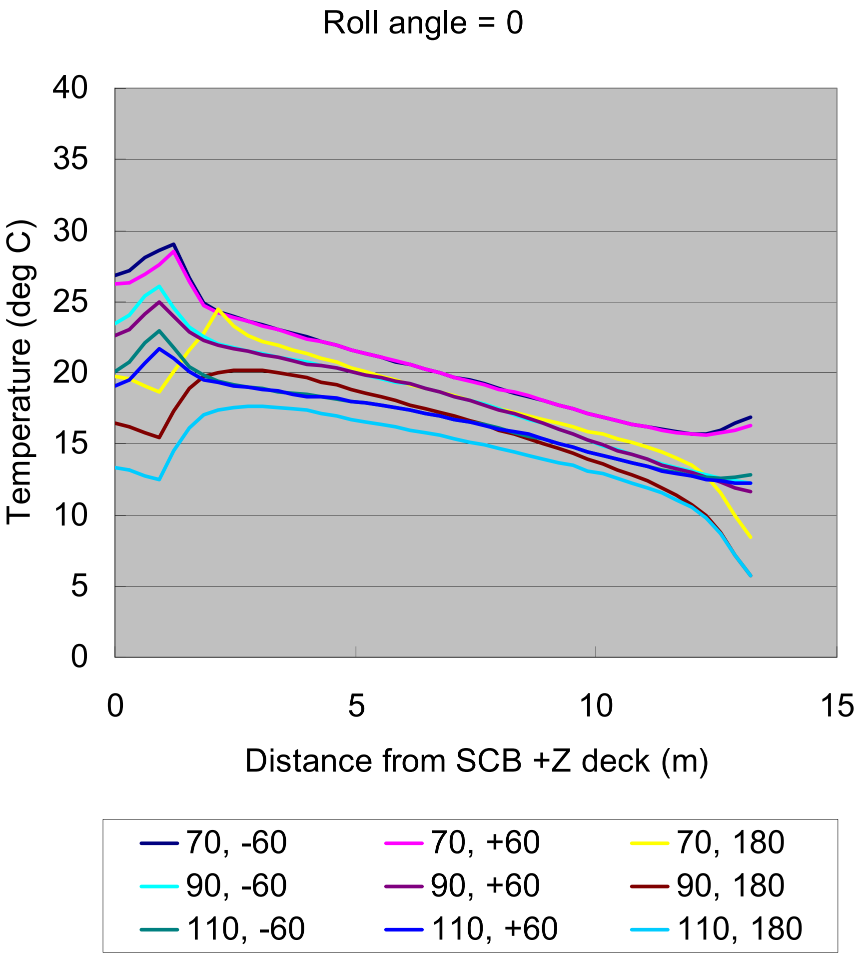
Thermal Distortion Analysis Cases

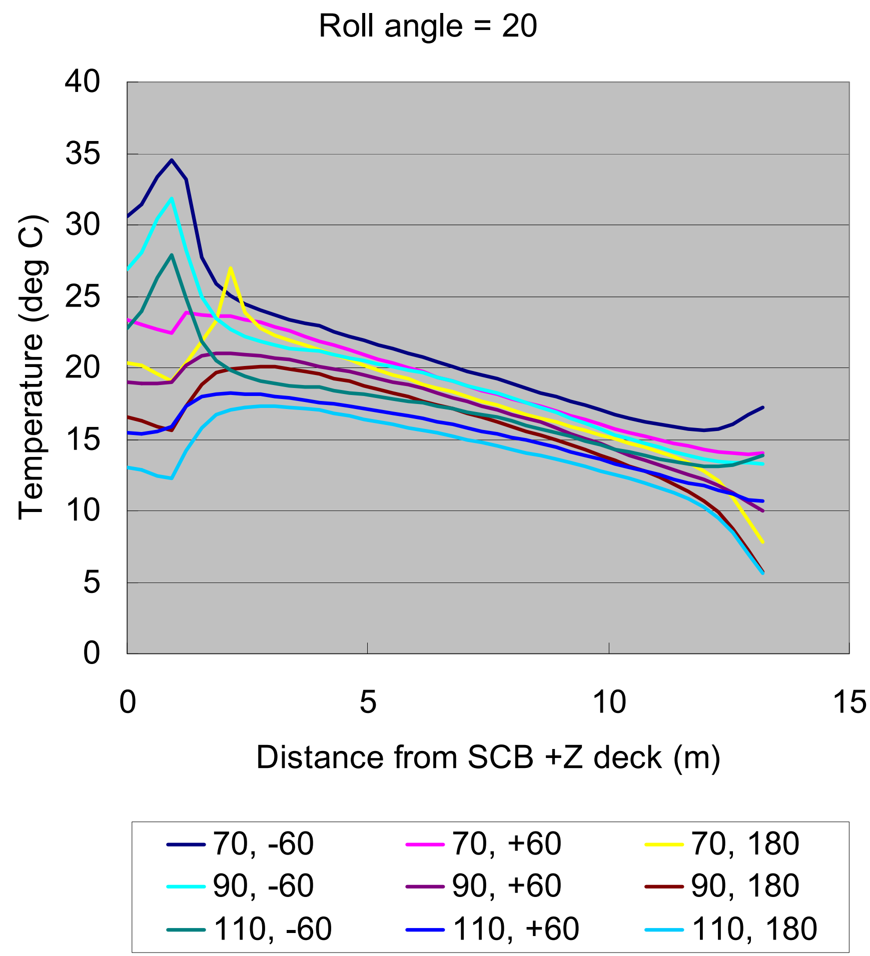
- 6 cases, steady state
  - Pitch = 90° ± 20°, Roll = 0
  - Pitch = 90° ± 20°, Roll = 20°
- Assume symmetry for -20° roll angle
- Numerical results provided for FMS, adapter, FMA structure, SC bus, and FIP.
  - Nodal temperatures specified as function of position

Thermal Distortion Analysis - Mast Temperatures



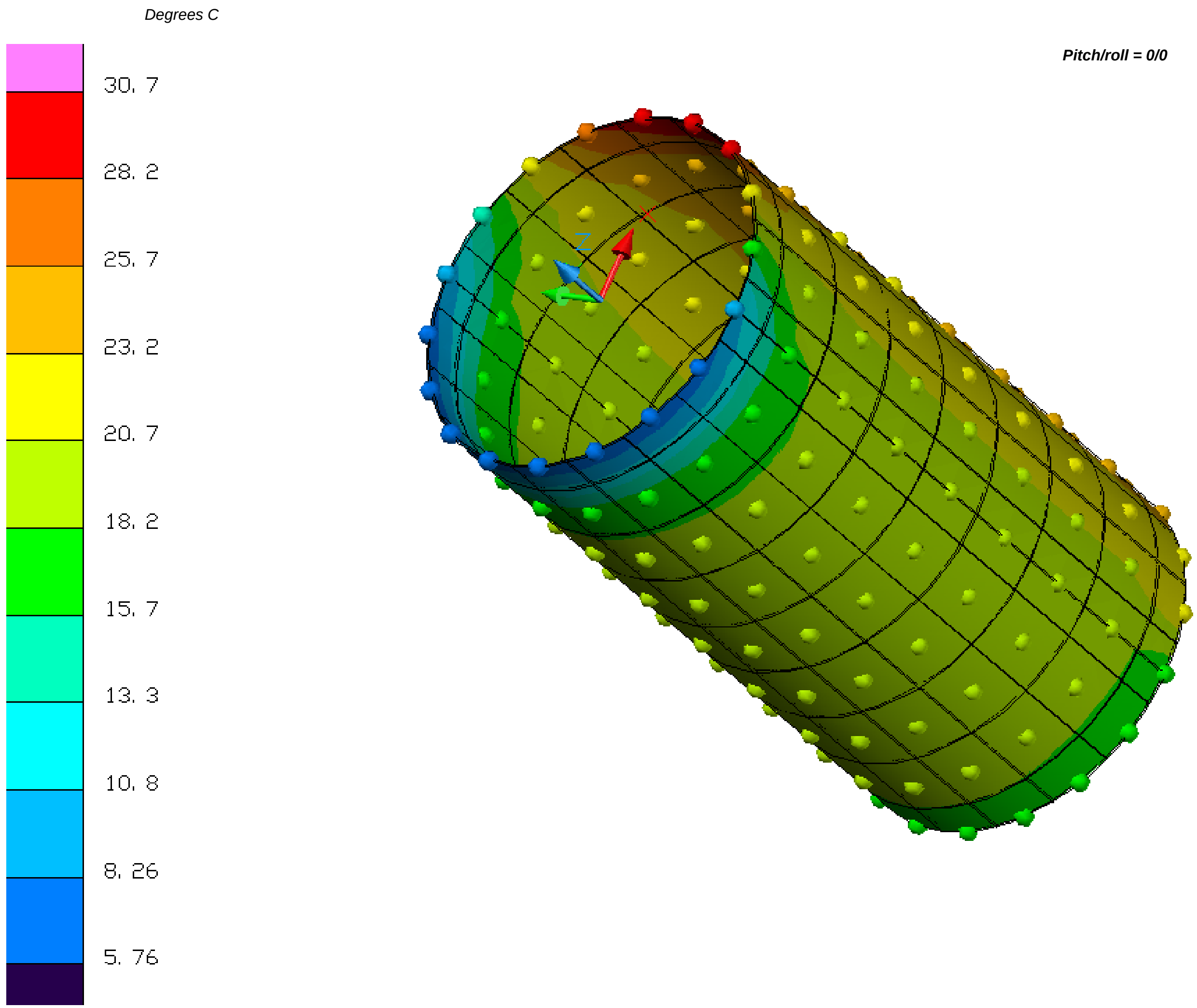
Thermal Distortion Analysis - Mast Temperatures, Numerical Results



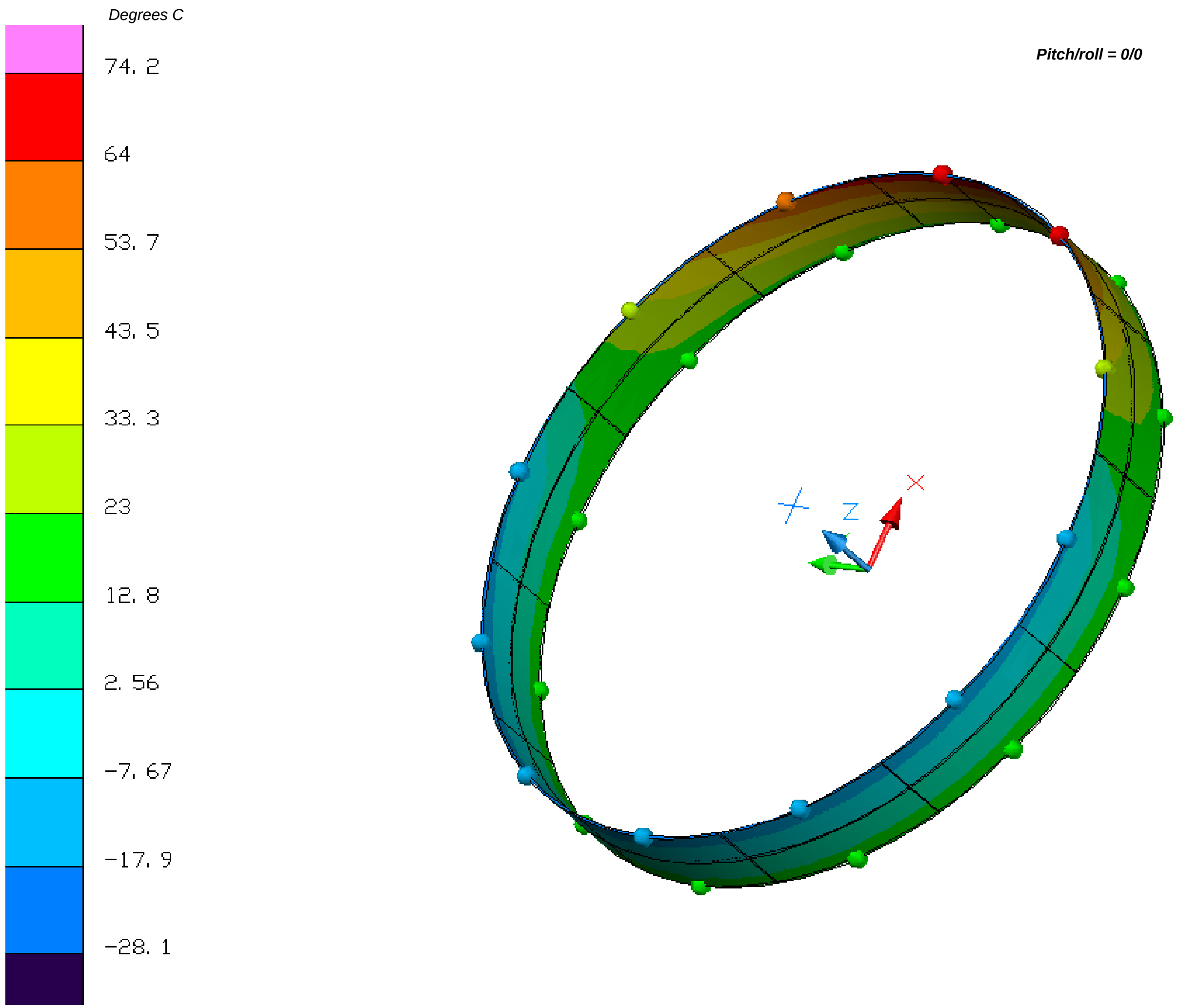


Legend: *First number is pitch angle, measured from telescope axis*
Second number is mast angular position, measured from +X axis

Thermal Distortion Analysis - FMS Temperatures



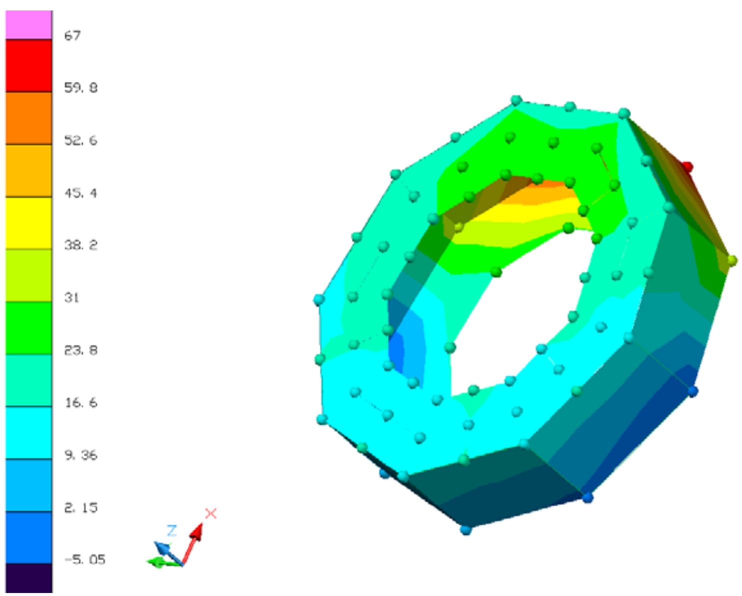
Thermal Distortion Analysis - PAF Temperatures

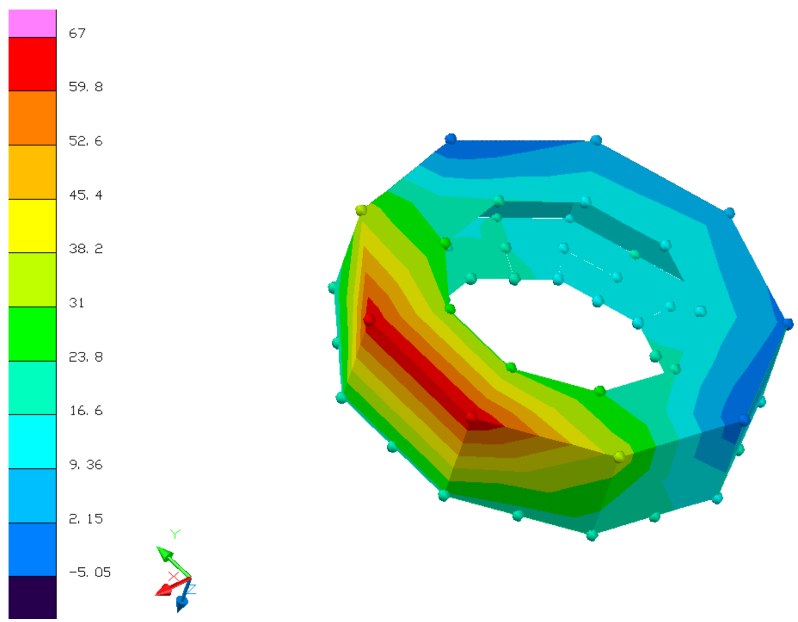


Thermal Distortion Analysis - Bus Structure Temperatures, +Z and –Z side

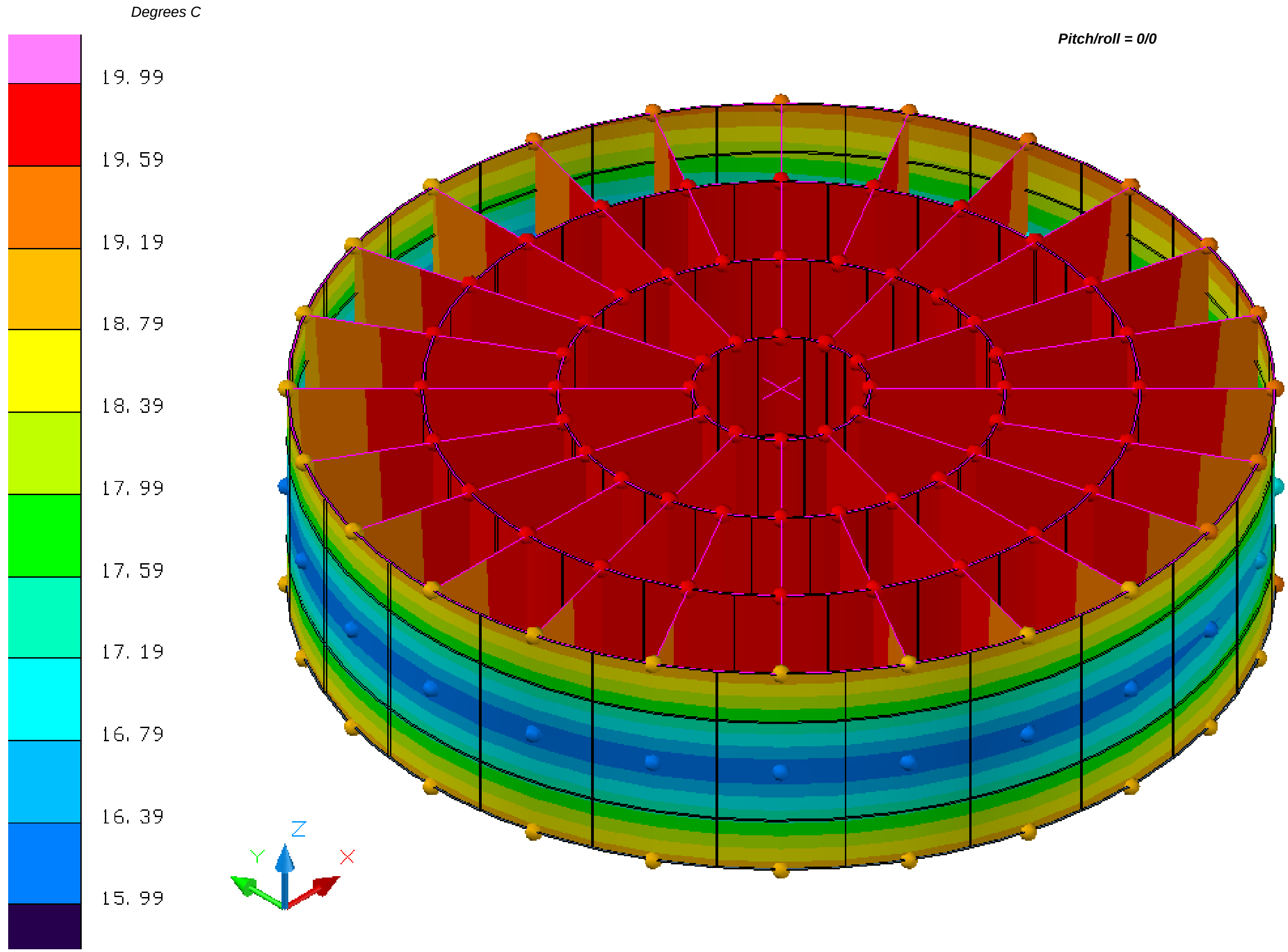
Pitch/roll = 0/0

Degrees C

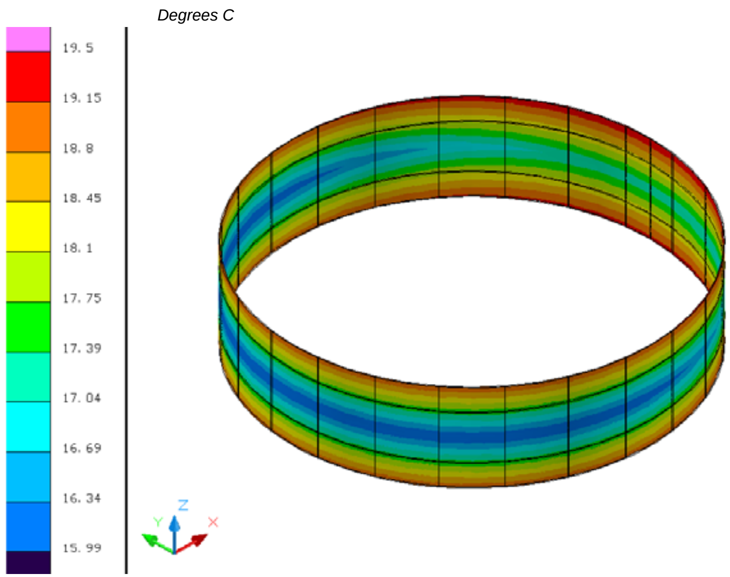


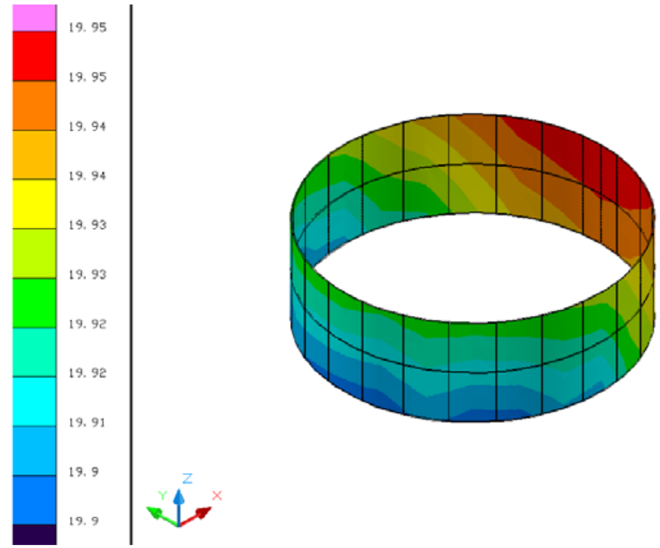


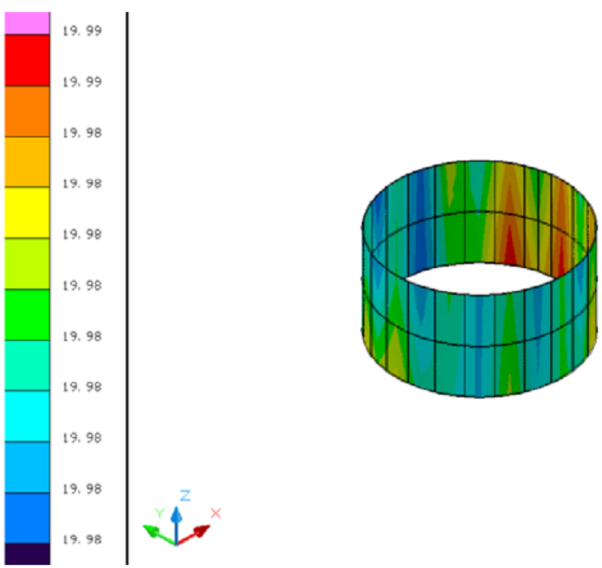
Thermal Distortion Analysis - FMA Temperatures

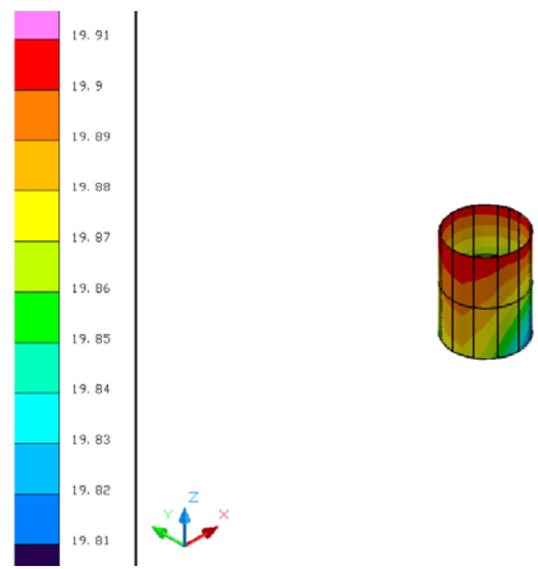


Thermal Distortion Analysis – FMA Ring Temperatures



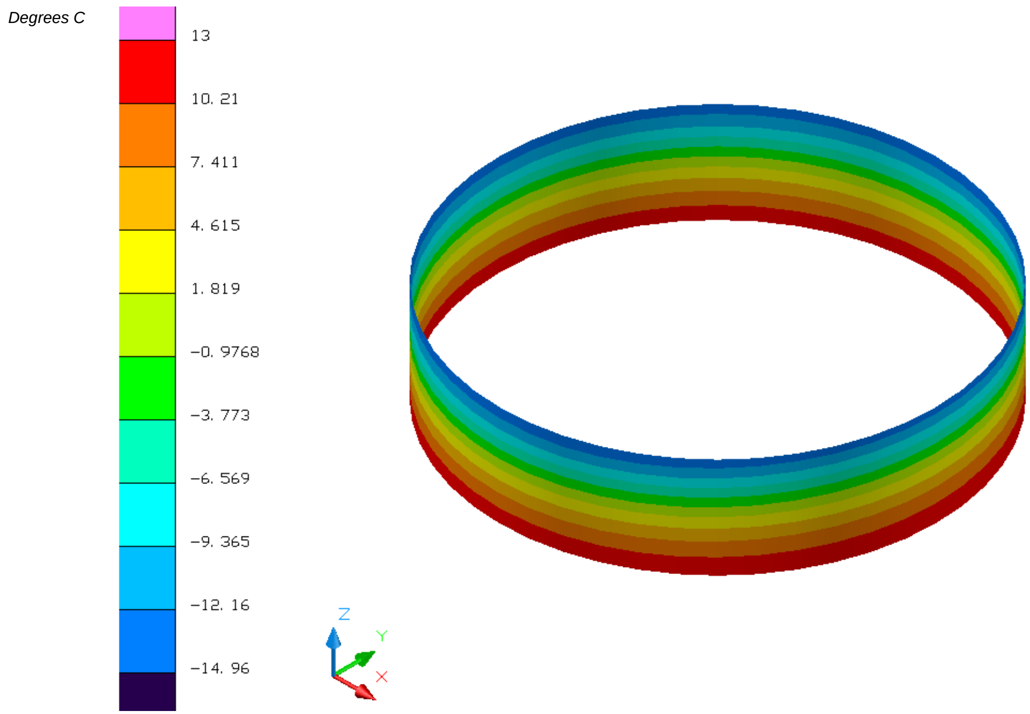






FMA Thermal Interface Analysis

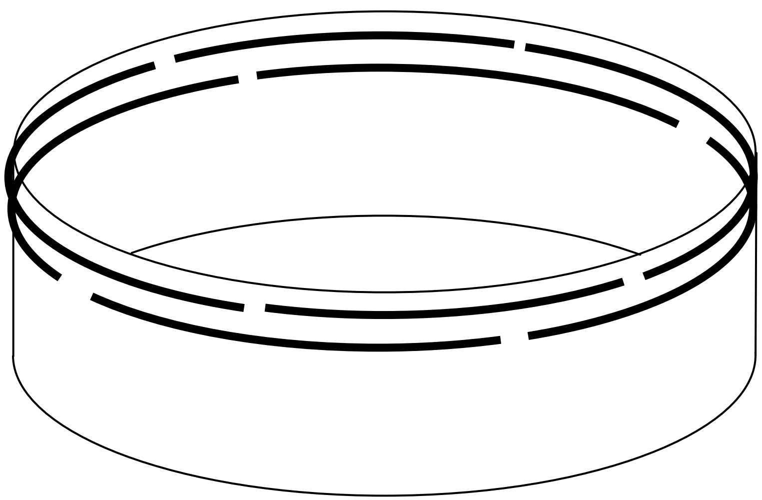
FMA Thermal Interface Modeling - Payload Adapter Temperature Distribution



- *Heat pipes at both ends*
- *Conductive silver composite coating, MLI outside*
- *Assume 3.2 mm thick*
- *No heaters on FMS*

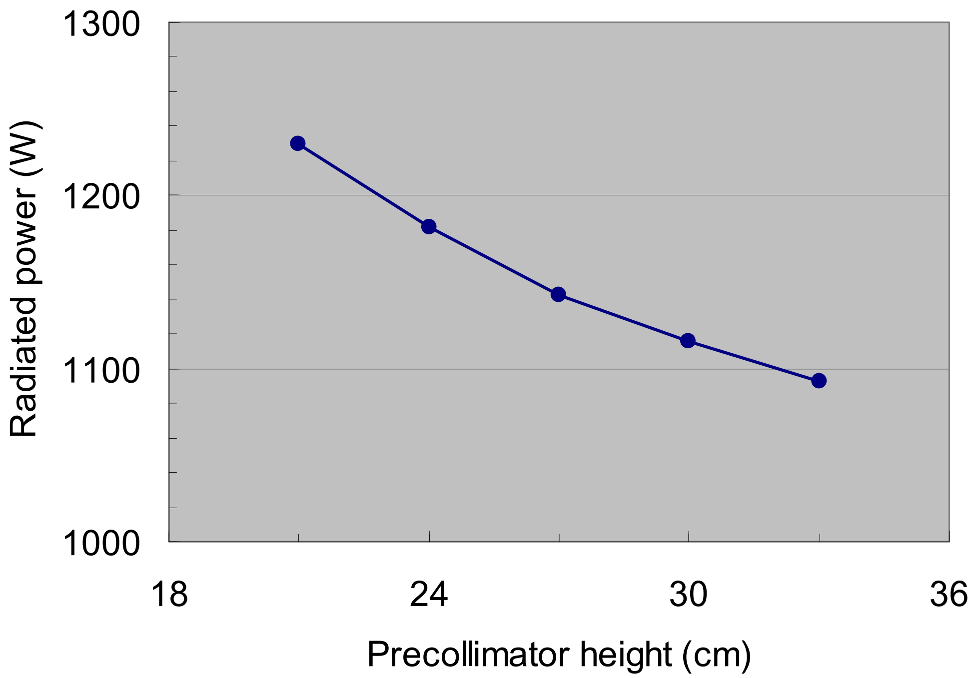
Observatory Model: Adapter Heat Pipe Configuration

- Typical heat pipe extrusion length is 10 ft.
  - Two rings with overlapping CCHPs provide redundancy, thermal continuity. HP size is ~0.5 in. square. Can be mounted inside.
  - Expect to use high conductivity adhesive, e.g., McGann Nusil CV2942
- Early calculations assume pipes are at –Z end.
  - To avoid gradients, can mount second set of pipes at other end of adapter.



FMA Thermal Interface Modeling - Heat Loss Through Precollimator, Effect of Precollimator Thickness

- **Black body surface behind precollimator, 20°C, mirror side inactive**
- **Exterior coatings:**
  - **Black Kapton on sunshade**
  - **25% second surface aluminized Kapton/75% bare aluminum on PAF and back of FMS**
  - **1 mil thick second surface aluminized Kapton on sun side of FMS**

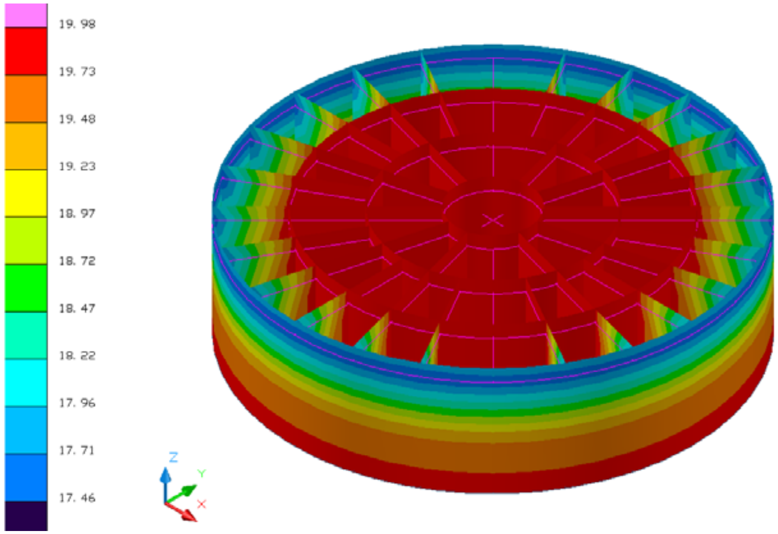


FMA Thermal Interface Modeling - Heat Loss Through Precollimator, Effect of Observatory Attitude

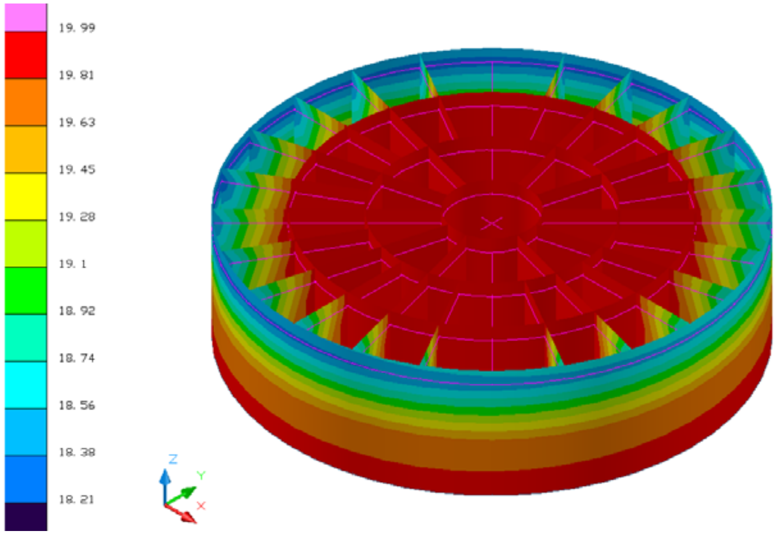
- **Black body surface behind precollimator, 20°C, mirror side inactive**
- **Exterior coatings:**
  - **Black Kapton on sunshade**
  - **25% second surface aluminized Kapton/75% bare aluminum on PAF and back of FMS**
  - **1 mil thick second surface aluminized Kapton on sun side of FMS**

Attitude		Heater power (W)		
Pitch	Roll	+Z face	modules	total
70	0	912	215	1127
90	0	901	187	1088
110	0	913	221	1133
70	20	902	202	1104
90	20	907	190	1097
110	20	921	227	1148
Precollimator height = 27 cm				

FMA Thermal Interface Modeling - FMA Structure Temperatures with Ag Composite Coating

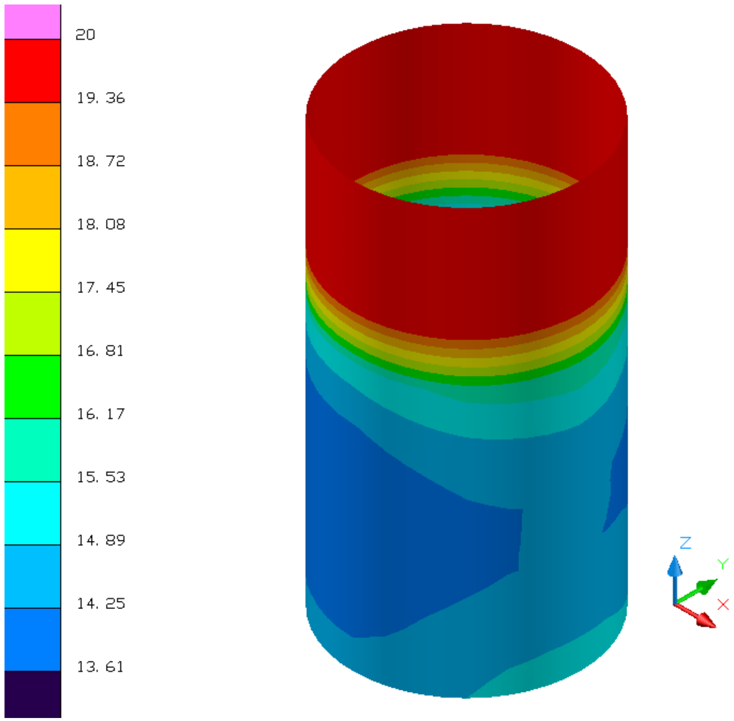


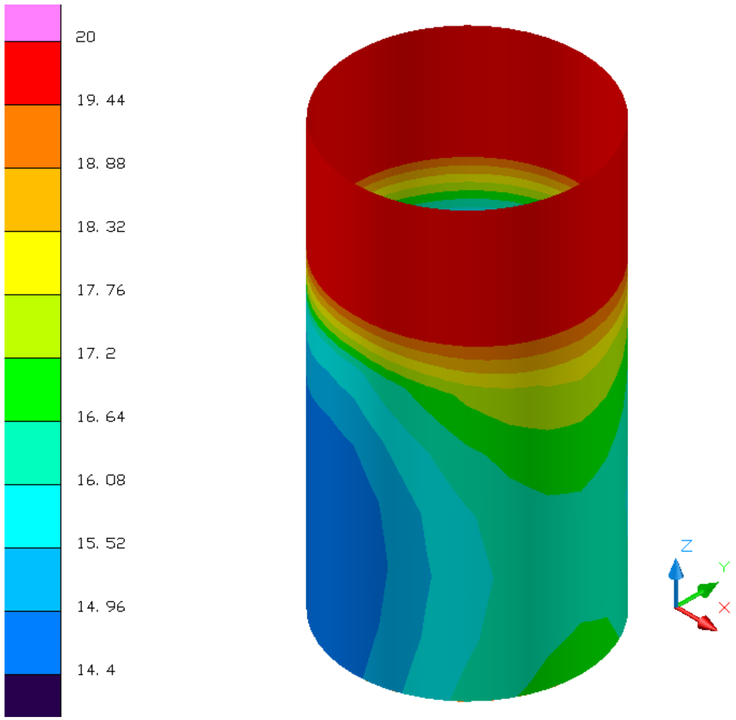
BOL, 17.46 – 19.98°C



EOL, 18.21 – 19.99°C

FMA Thermal Interface Modeling - FMS Temperatures with Ag Composite Coating

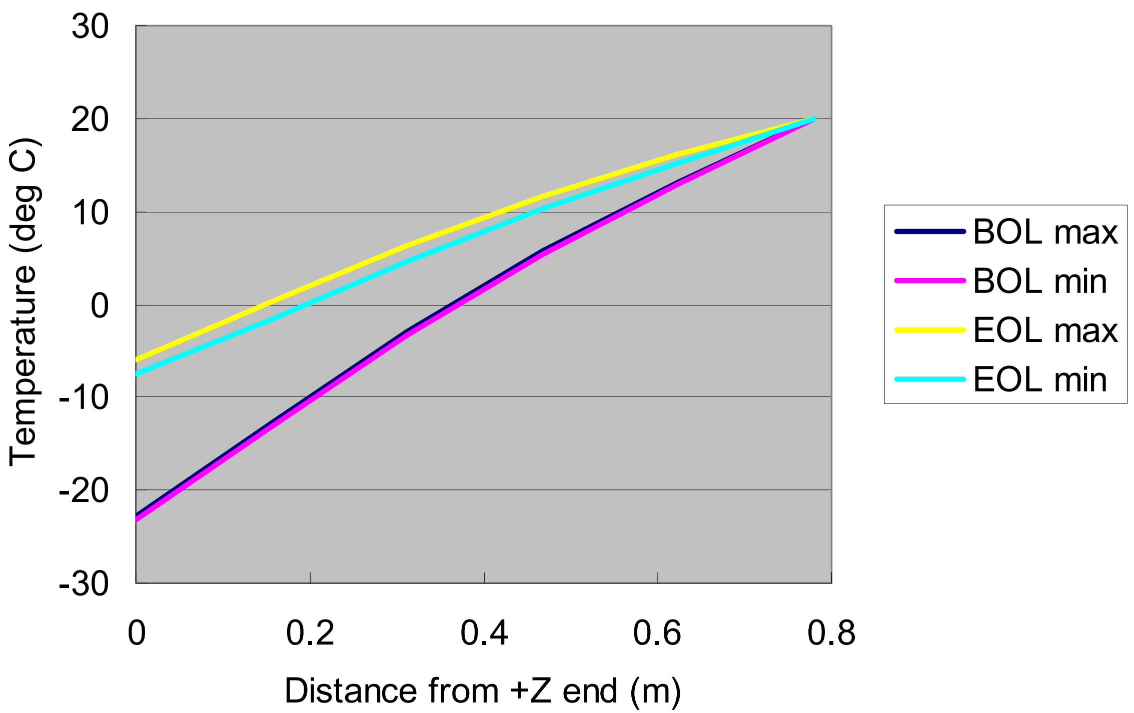




BOL, 13.61 – 20.00°C

EOL, 14.40 – 20.00°C

FMA Thermal Interface Modeling - Payload Adapter Temperatures with Ag Composite Coating



- *Heat pipes at both ends*
- *Conductive silver composite coating, MLI outside*
- *Assume 3.2 mm thick aluminum*

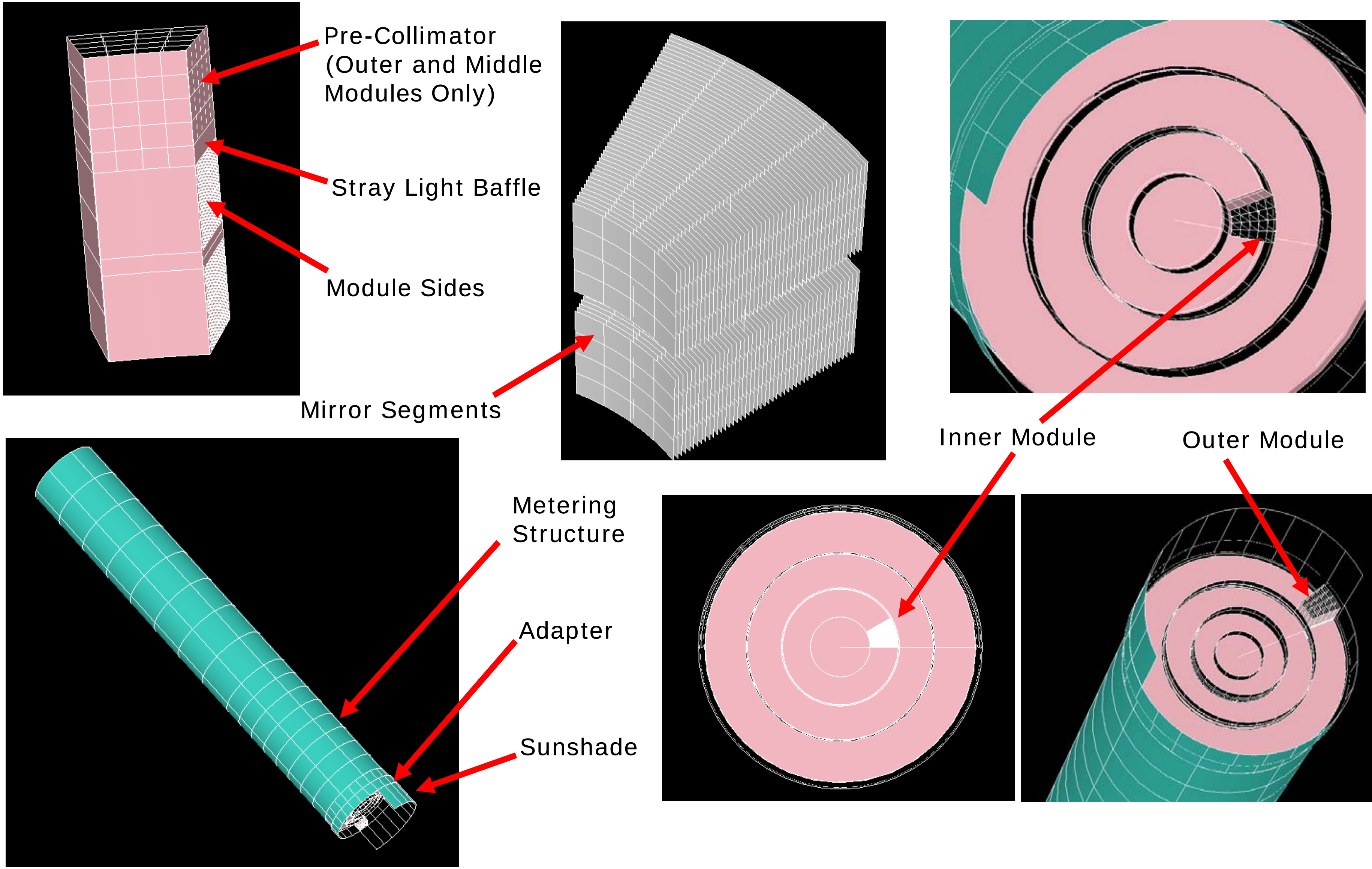
FMA Thermal Interface Modeling - Heat Loss with Ag Composite Coating

- Conductive silver composite coating on exterior surfaces of FMS, adapter, and sunshade, a/e = .08/.6 BOL, .25/.58 EOL. Black inside, e = .8
- MLI outside FMS and adapter, e* = .02
- Mirror modules black, radiation coupling to frame components. Heaters on module surfaces, 20 ± 1°C setpoint
- FMS heaters on 1.59 m length at +Z end, 20 ± 1°C setpoint
- Heat loss through precollimator calculated assuming constant temperature 20°C surface behind precollimator

	BOL	EOL
Through precollimator	1072	1029
Mirror modules	164	116
FMS heaters	237	176
Total	1473	1321

FMA Thermal Modeling

FMA Thermal Modeling / Assumptions



FMA Thermal Modeling / Assumptions

- Each mirror module has its own heater control and is thermally independent of other modules
- Each mirror segment has 16 nodes on each side
- Only one module is included in thermal model at a time for temperature predictions due to very large number of surfaces of all 60 modules and size of radiation couplings
  - Nearly 5 million radiation couplings for one module and file is larger than 300K KB
  - A different model for inner, middle or outer modules
  - Total heater power is calculated for all 60 modules based on number of modules and heater power for each module
- Mirror is thin glass and coating is iridium
  - Very low thermal conductivity (~1 $Wm^{-1}K^{-1}$)
  - Emittance is 0.05 and specular
- Backside of mirror is glass with no coating (high emittance) due to stray light
- Conduction path from mirror segments to module enclosure is very low

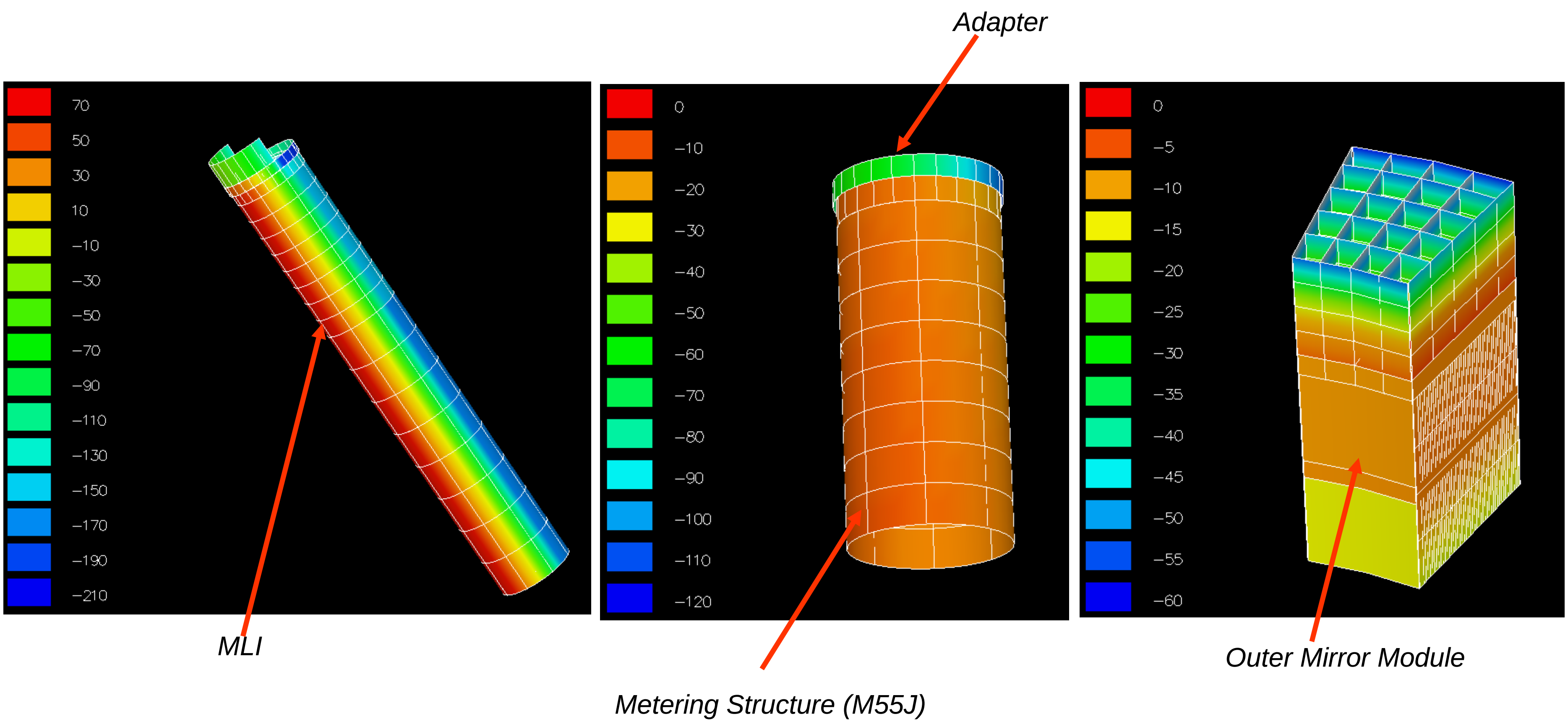
FMA Thermal Modeling / Assumptions

- Pre-collimator has very low thermal conductivity
  - Fiberglass, G-10, etc.
- Interior of metering structure has a high emittance to enhance heat radiation from sun side to anti-sun side
- Anti-sun side of sunshade is black Kapton
- Heater controllers have ±0.1°C tolerances or better

	BOL		EOL (5 Years)	
Coating	Absorptance	Emittance	Absorptance	Emittance
Conductive Silver Composite	0.08	0.60	0.25	0.58
Germanium Kapton	0.45	0.78	0.56	0.76

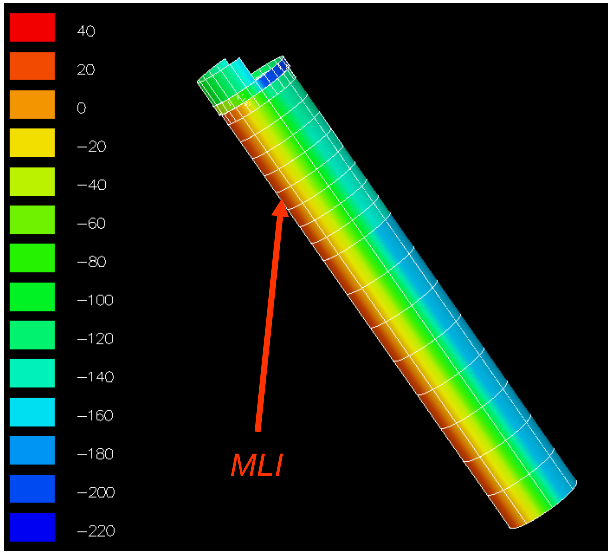
FMA Thermal Predictions

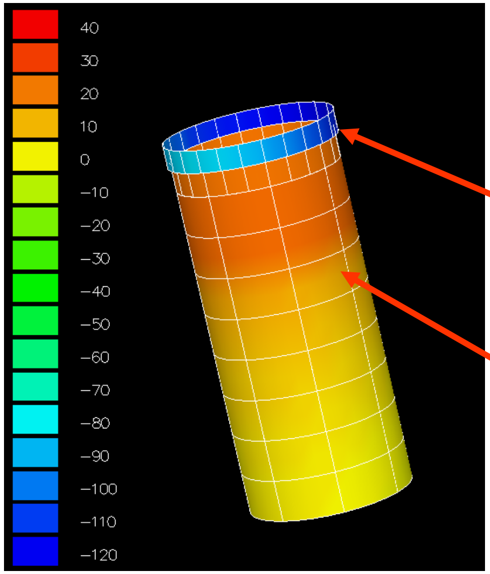
Worst Hot Case, No Active Heater Control, Sufficiently Cold Biased.
Temperature in °C



FMA Thermal Predictions

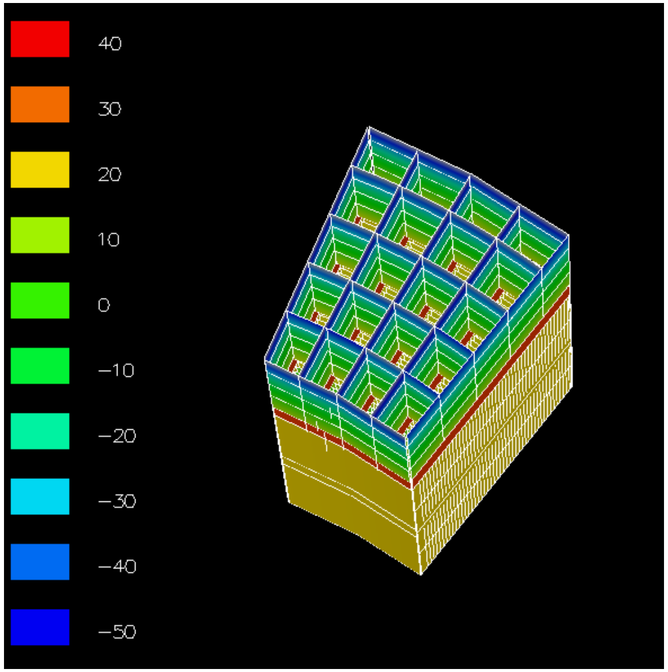
Worst Cold Case, Active Heater Control
Temperature in °C





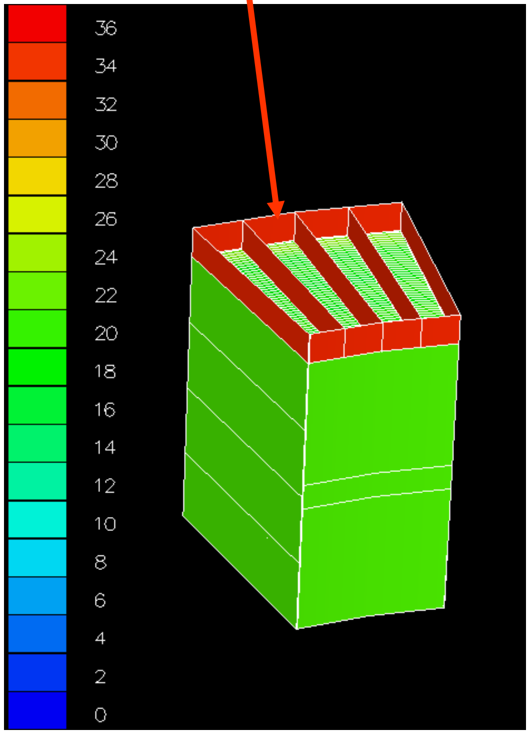
Adapter

Metering Structure (M55J)



Outer Module

Active Heater Control



FMA Heater Power Predictions

	Heater Power (W)*
Outer Modules	650
Middle Modules	360
Inner Modules	100**
Metering Structure	420
Total	1530

**BOL worst cold case.*
***A thin aluminized Kapton layer on top of stray light baffle. Aluminum side facing optics.*

FMA Heater Controller, Heater and Harness Mass Estimate

	Harness Mass (kg)	Heater Mass (kg)	Thermistor Mass (kg)	Heater Controller (kg)
Outer Modules	9	14	0.3	40
Middle Modules	6	9	0.2	26
Inner Modules	3	5	0.1	14
Metering Structure	1	9	0.2	5
Subtotal	19	37	0.8	85
Total	142 kg			

Redundancy included.

.

FMA Thermal Modeling Analysis Conclusions

FMA Thermal requirements met:

- The FMA is kept within its 20 +/- 1C requirement by
  - Utilizing FMA Cold bias + FMA Heaters for FMA thermal control
  - Iso-thermalizing the Spacecraft Adapter using heat pipes
  - Controlling the temperature of the +Z end of the Fixed Metering Structure (up to a distance of 1.5 m from the FMA) to 15C
- Only conventional thermal control techniques are required

Observatory Finite Element Model

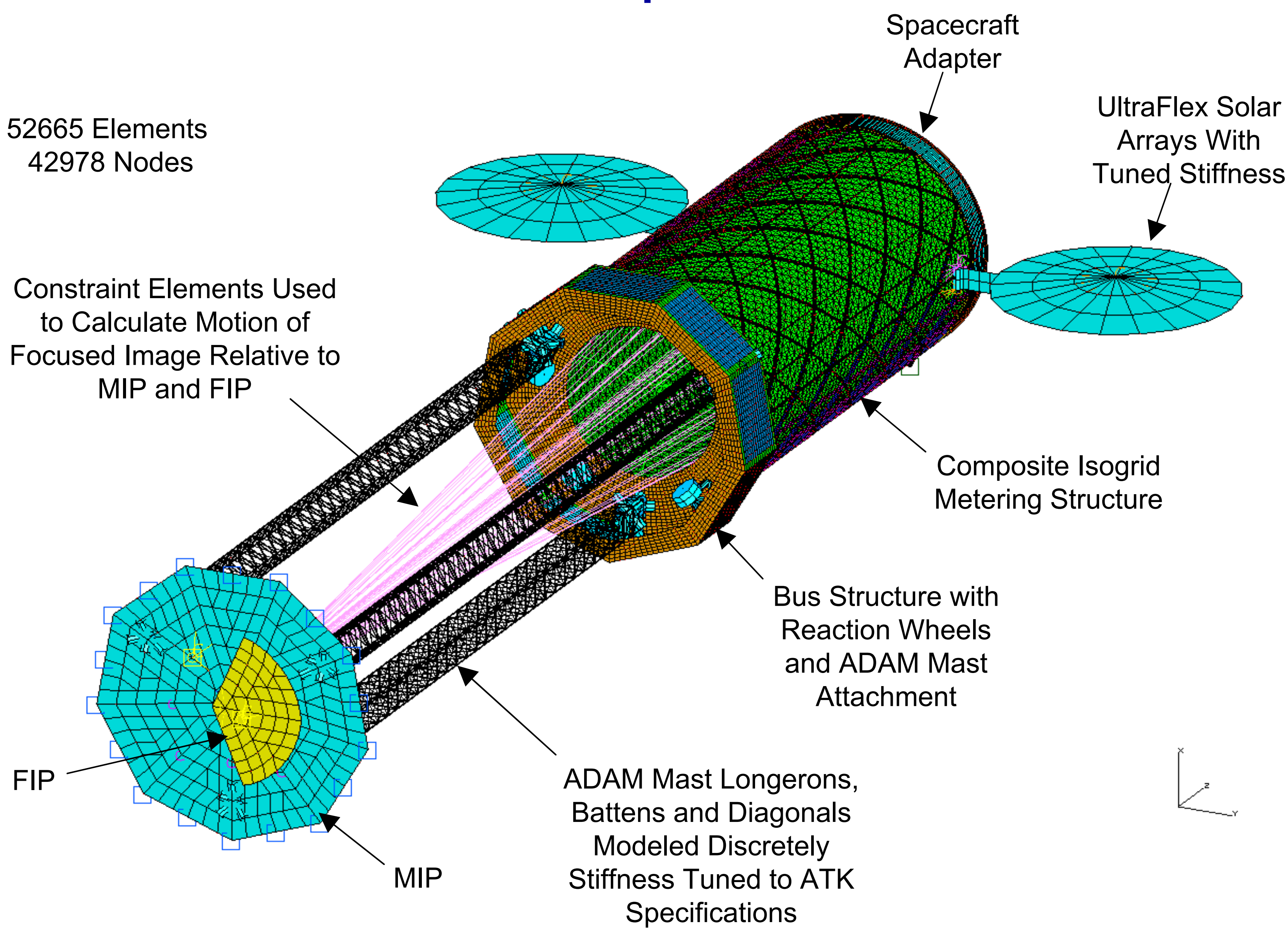
Modeling Applications

- **Finite Element Model was used for:**
  - **Modal Analysis**
  - **Jitter Analysis**

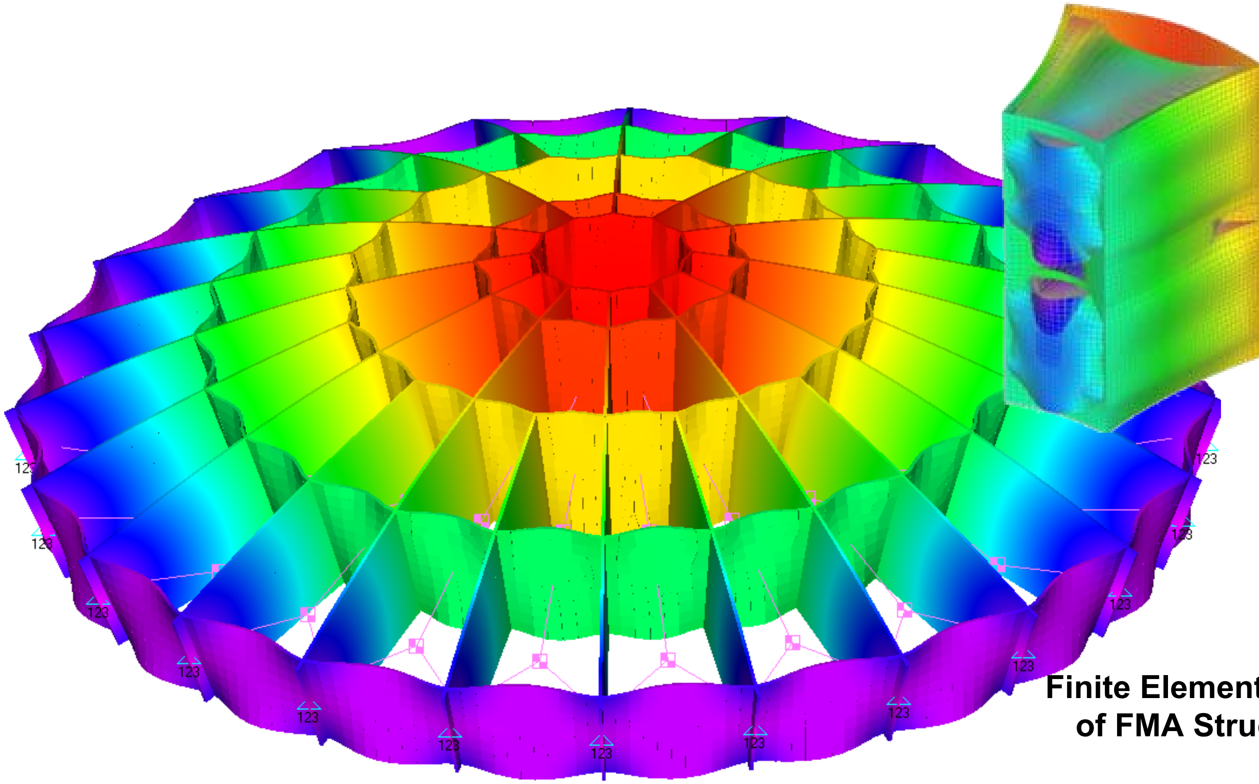
Pre- and Post-processing Using IDEAS MS12

Static and Dynamic Model Solution Using NASTRAN NX2.0 and 5.1

Finite Element Model Description



NASA FMA FEM



Finite Element Model
of FMA Structure

Modal Analysis

Mode Shapes and Frequencies

Mode Number	Frequency (Hz)	Description
1	0.60	SA Boom Y-Bending, Anti-Symmetric
2	0.60	SA Boom Y-Bending, Symmetric
3	1.04	SV Torsion
4	1.52	SV Bending (Y) and SA Boom Torsion Sym (1 of 2)
5	1.54	SV Bending (X) and SA Boom Torsion Antisym (1 of 2)
6	1.55	SV Bending (Y) and SA Boom Torsion Sym (2 of 2)
7	1.56	SV Bending (Y) and SA Boom Torsion Sym (2 of 2)
8	2.21	SA Boom 2nd Y-Bending, Symmetric
9	2.21	SA Boom 2nd Y-Bending, Anti-Symmetric
10	7.26	FIP Y-Bending
11	8.28	SA Boom X-Bending, Symmetric
12	8.47	SA Boom X-Bending, Anti-Symmetric
13	8.87	FIP X-Bending
14	9.34	FIP XY-Bending
15	10.50	Mast Bending
16	10.52	Mast Bending
17	10.70	Mast Bending
18	10.84	Mast Bending
19	12.14	MIP Y-rotation
20	14.79	SV Axial + MIP and FIP X-Rotation

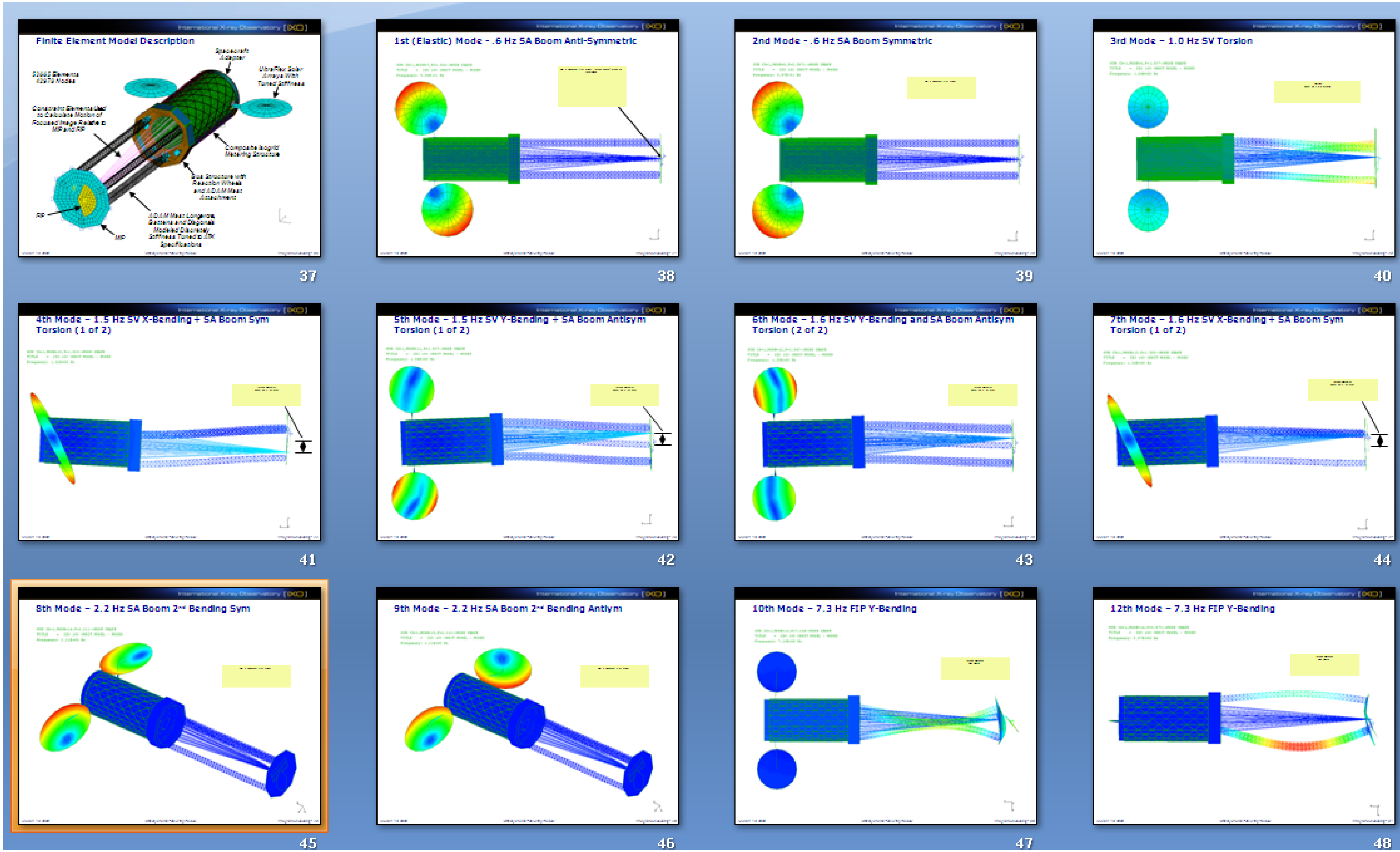
Low mass participation
Low mass participation

Preliminary analysis shows that the stowed 1st bending mode frequency is ~ 12.0 Hz

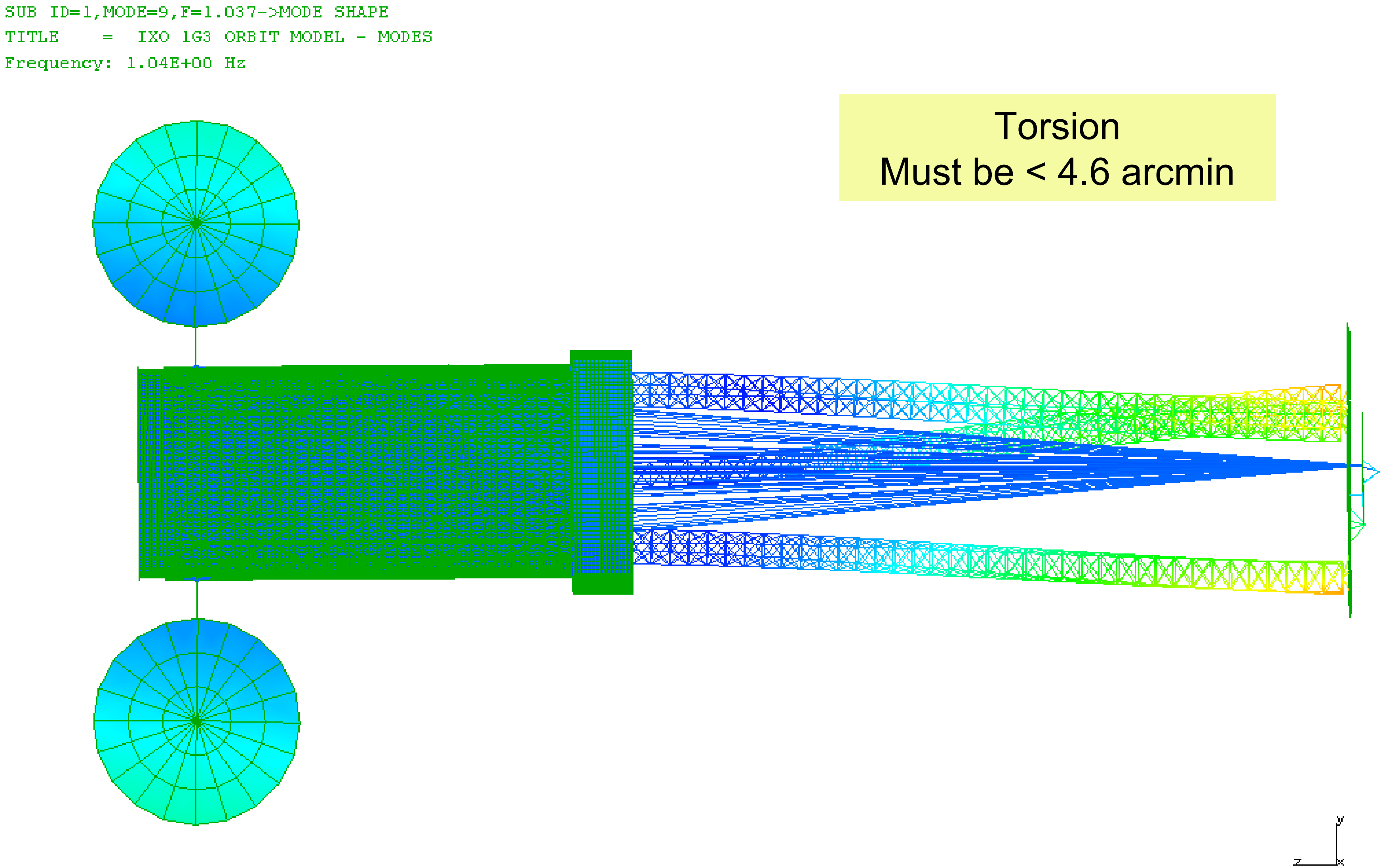
With contingency deployment on two masts, the 1st bending mode drops to 0.74 Hz and torsion to 0.70 Hz.

- 1st Bending and Torsion mode frequencies satisfy IXO's requirements

Mode Shapes and Frequencies

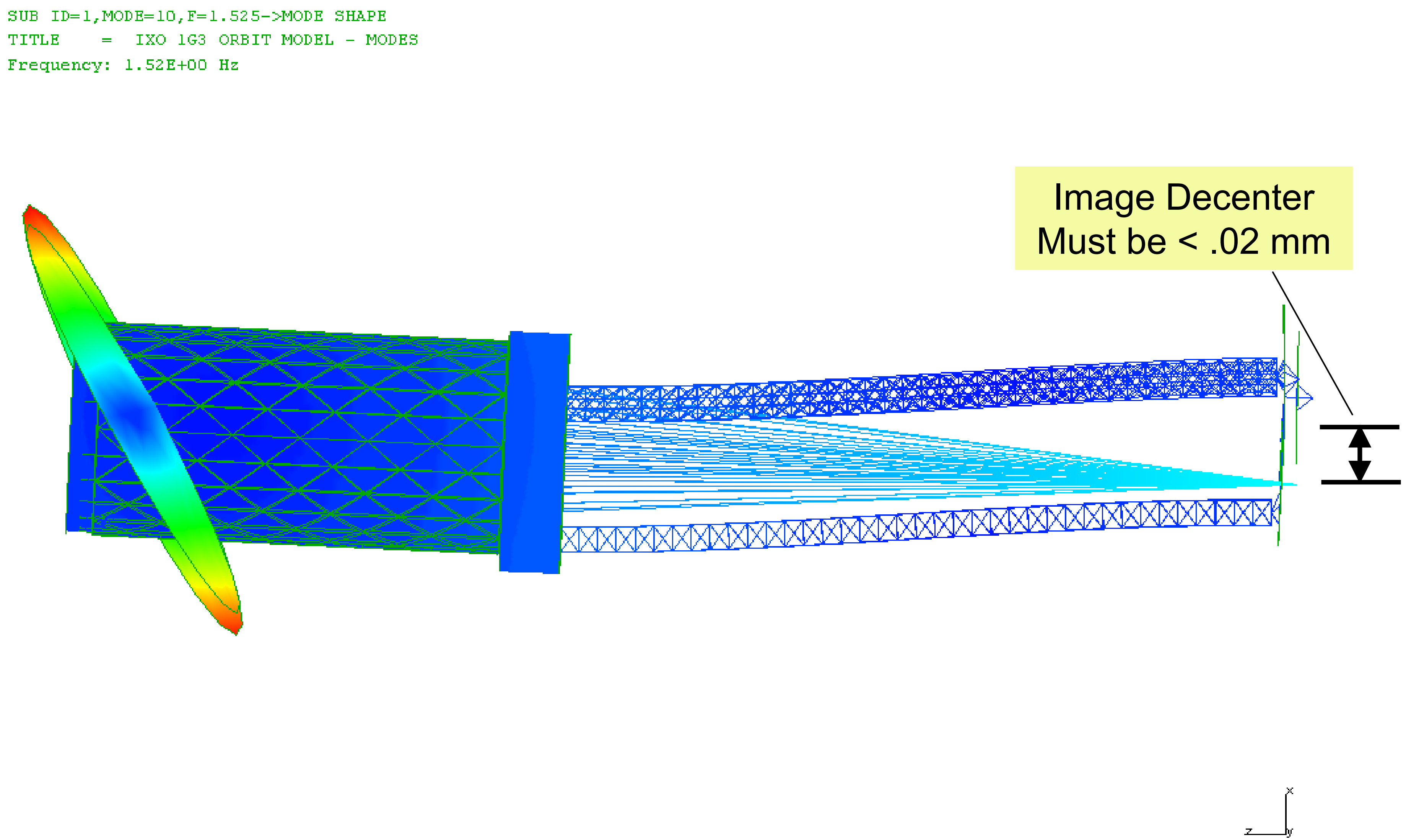


3rd Mode – 1.0 Hz SV Torsion



Torsion
Must be < 4.6 arcmin

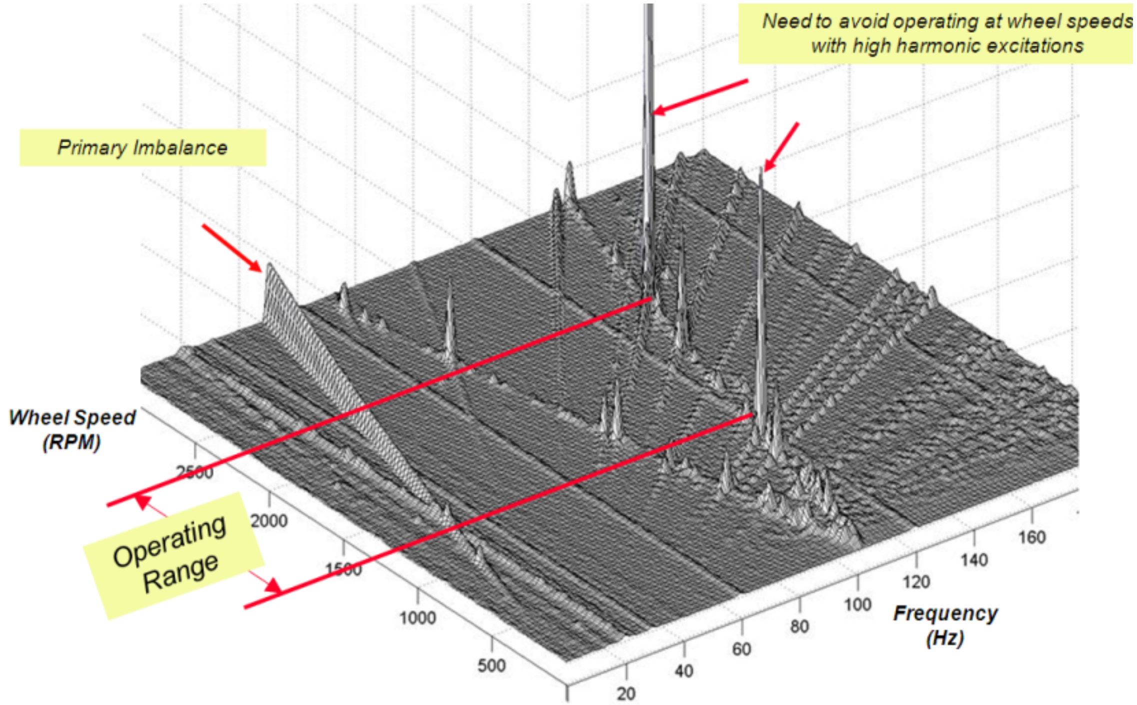
4th Mode – 1.5 Hz SV X-Bending + SA Boom Sym Torsion



Jitter Analysis

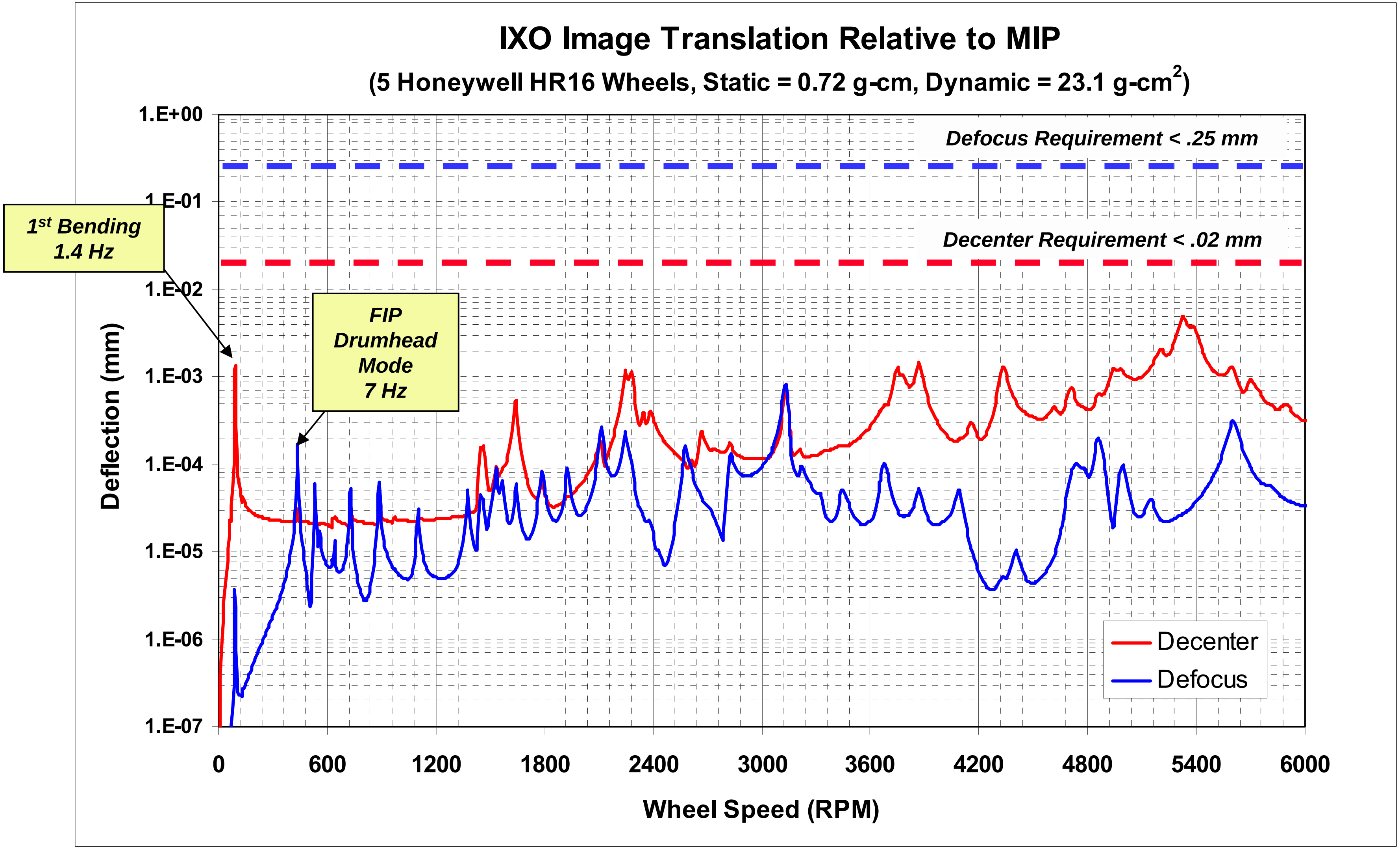
Jitter Analysis Parameters

- 150 N-m-s HR16 Wheel Imbalances (derived from datasheet)
  - Static = .72 g-cm, Dynamic = 23.1 g-cm^2
  - Only primary imbalance considered
  - Refined analysis will include affects of higher harmonics
- Use 0.5% modal damping
- Apply disturbances to all 5 wheels
  - RSS all wheels (conservative: assumes all wheels operate at same speed)
  - Calculate optical element jitter and LOS pointing error versus wheel speed

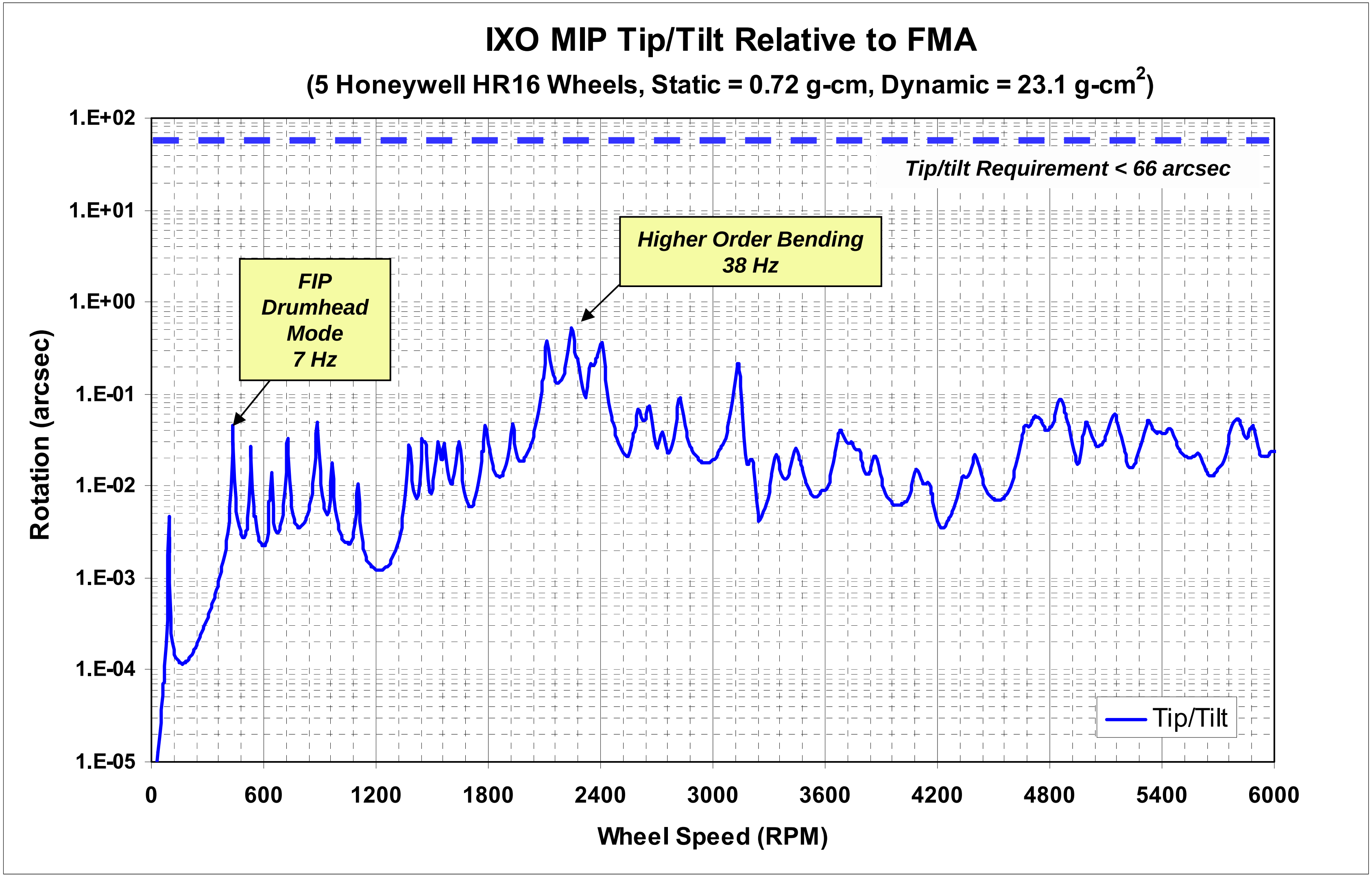


Example Carpet Plot of In-plane Imbalance Forces From HR14 Dynamic Test

Jitter Analysis Results

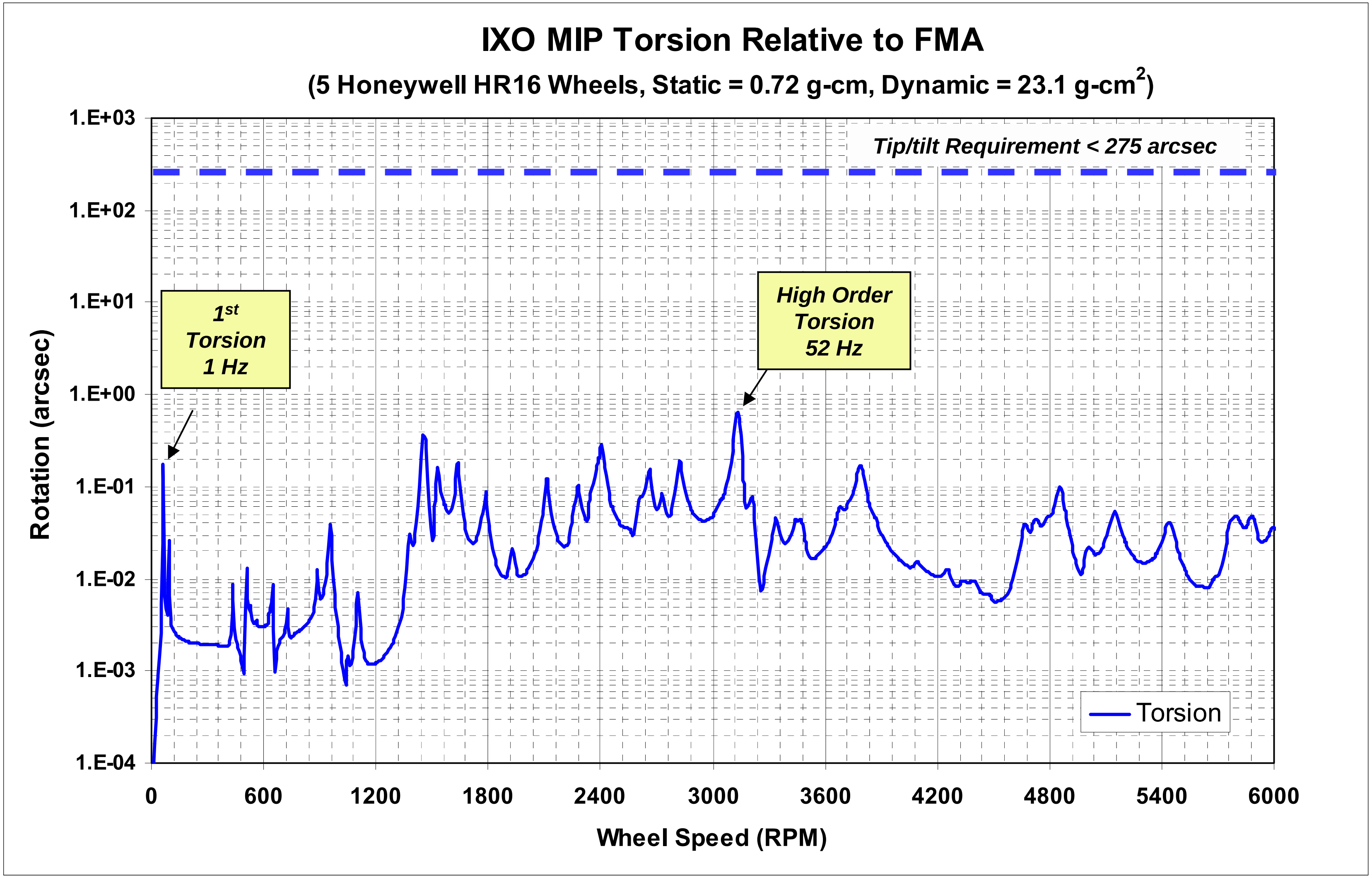


Jitter Analysis Results (Tip / Tilt)

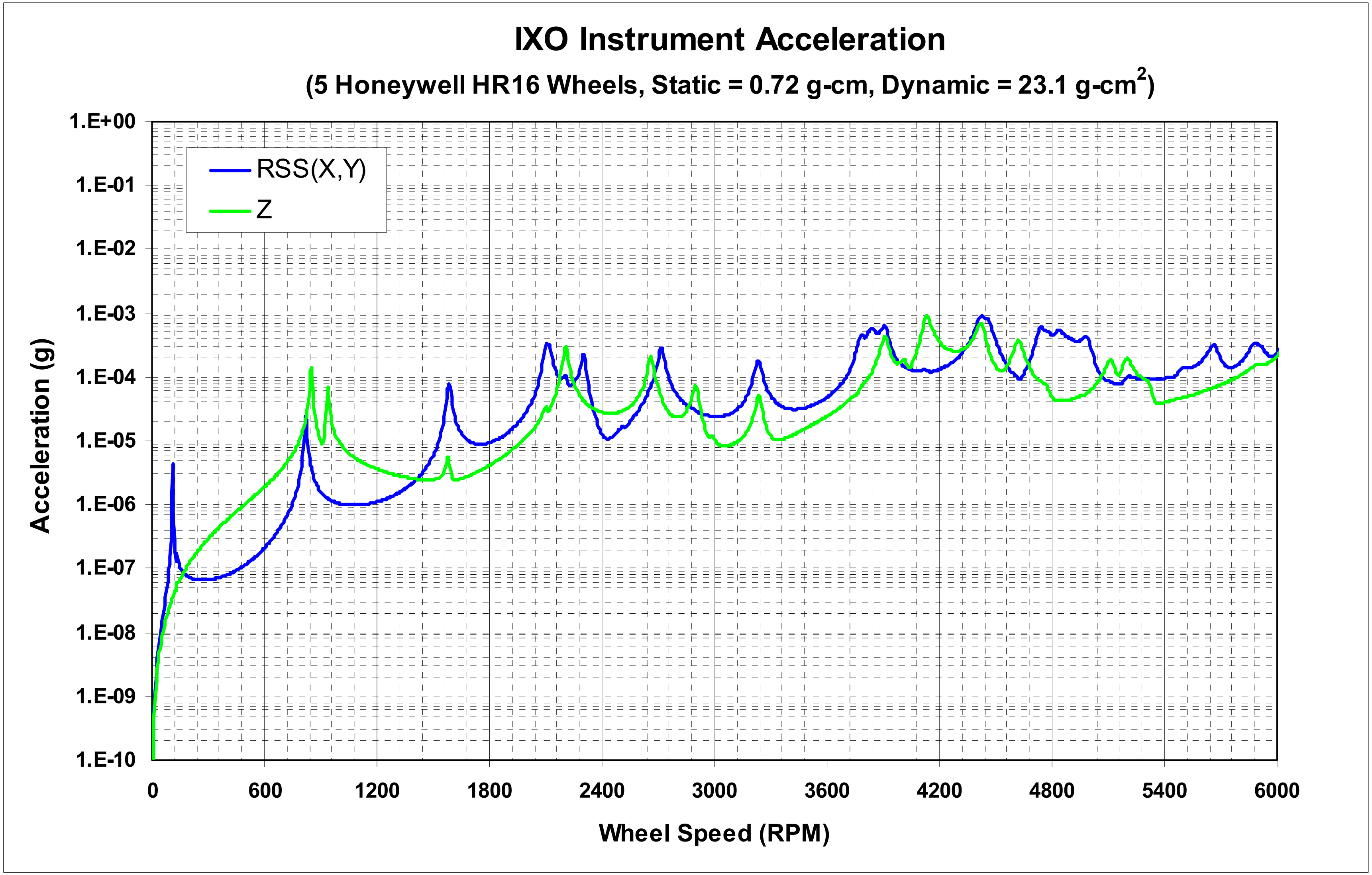


Responses << Requirement

Jitter Analysis Results (Torsion)



Instrument Accelerations



Peak Acceleration = 1000 micro-g (at 60 – 80 Hz)

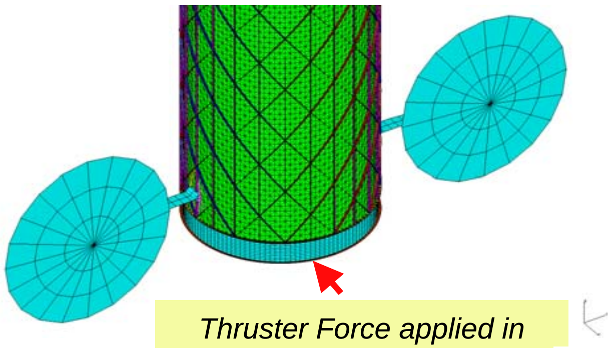
Integrated Modeling

Modeling Applications

- Integrated Models were used for:
  - Integrated Thruster Firing Disturbance Analysis
  - Integrated Thermal Distortion Analysis: Thermal + FEM

Integrated Thruster Firing Analysis

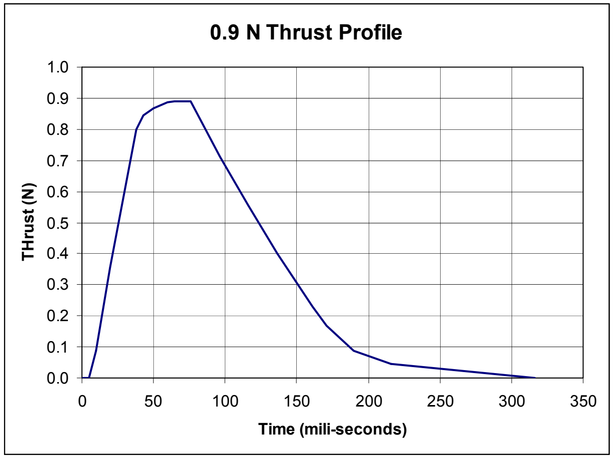
0.9 N Thruster Force



Thruster Force applied in the anti-sun direction, radially inward at the Spacecraft Adapter Flange

- **Use 2 sets of two .9 N thrusters spaced at +/-20 deg azimuth to place thrust vector on sunline even at roll angles other than zero**
- **Attitude Deviation versus Pulse Length**
  - **0.11 s burn* every 18 minutes: 0.165 arcsec deviation**
    - *** When calculated as thrust from a single 0.9 N Thruster on the X axis. For sum of two vectors from thrusters at +20 and -20 deg azimuths, adjust accordingly**
- **Modeling assumes IXO config with two 3.4 m dia Circular Ultraflex Solar Arrays**

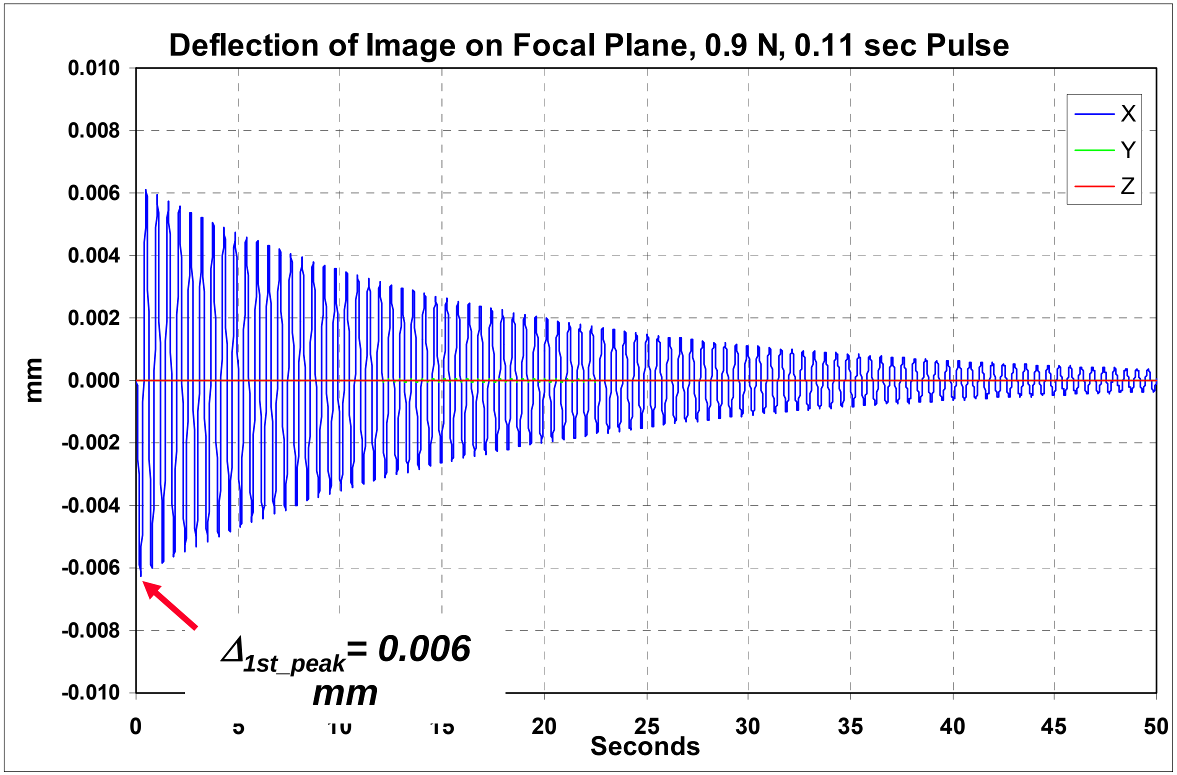
0.9 N Thruster Pulse and Model Parameters and Induced Vibration Decay



Total Impulse = 0.1 N-s
Derived from Astrolink jitter analysis profile

- **Modal damping = .5% of critical damping**
- **232 modes included in solution space (0 to 150 Hz range)**
- **2500 time steps at .001 second per step**

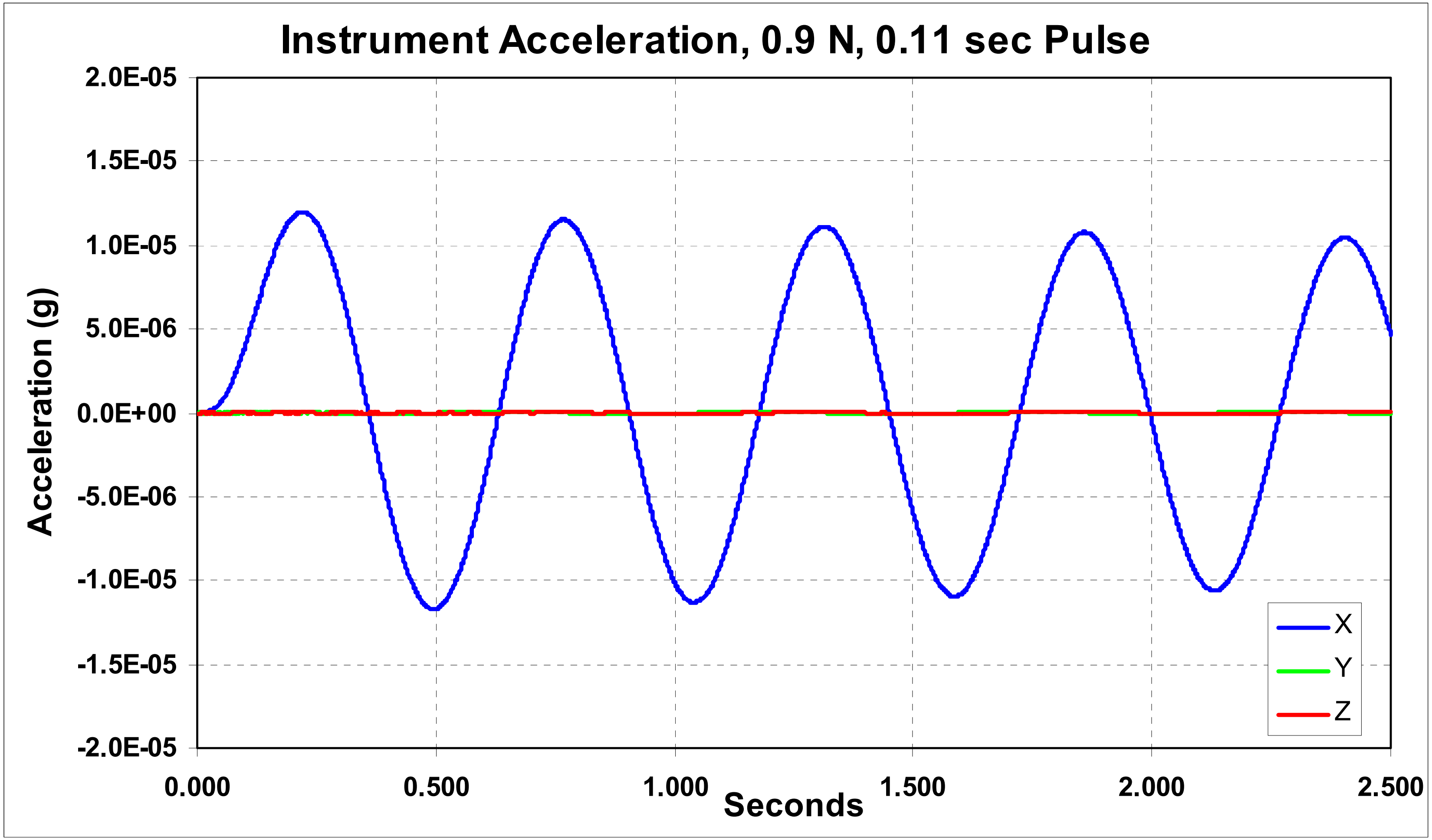
Deflection Decays to less than .001 mm after 30 seconds



$$\frac{\Delta_{nth\_peak}}{\Delta_{1st\_peak}} = e^{-2\pi n\xi/(1-\xi^2)^{1/2}} \Rightarrow \Delta_{peak\_at\_time\_t} = 0.006e^{-.0575t}$$

Integrated FEM + Control System Result

Accelerations due to 0.9 N Thruster Firing

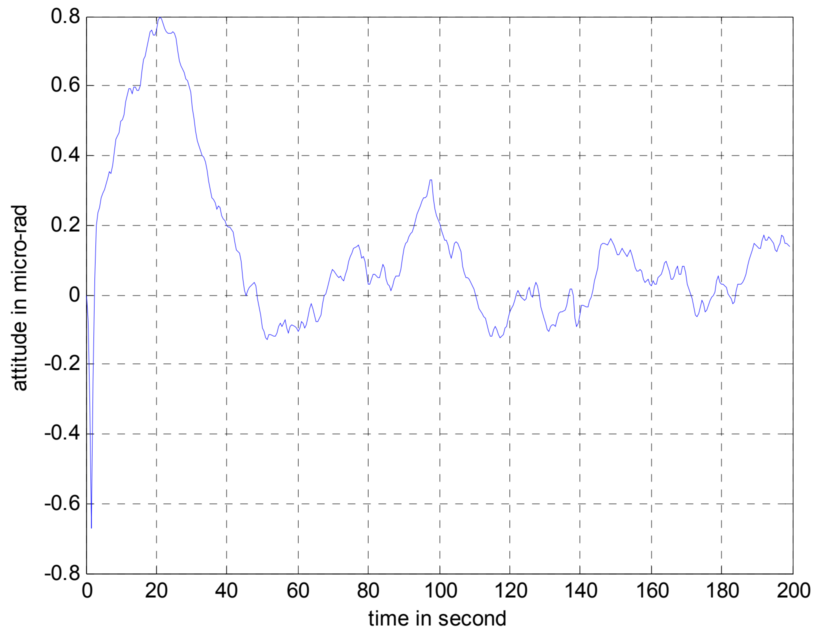


Peak Acceleration = 12 micro-g

Integrated FEM + Control System Result

Temporary Attitude Deviation due to 0.9 N Thruster Firing

- 0.9 N Thruster on for 0.11 s; generates 0.1 Ns impulse and 0.62 Nms angular momentum delta
- RWL feed forward of -0.2 Nm for 3.1 seconds
- Thruster firing centered relative to 3.1 second RWL feed forward period



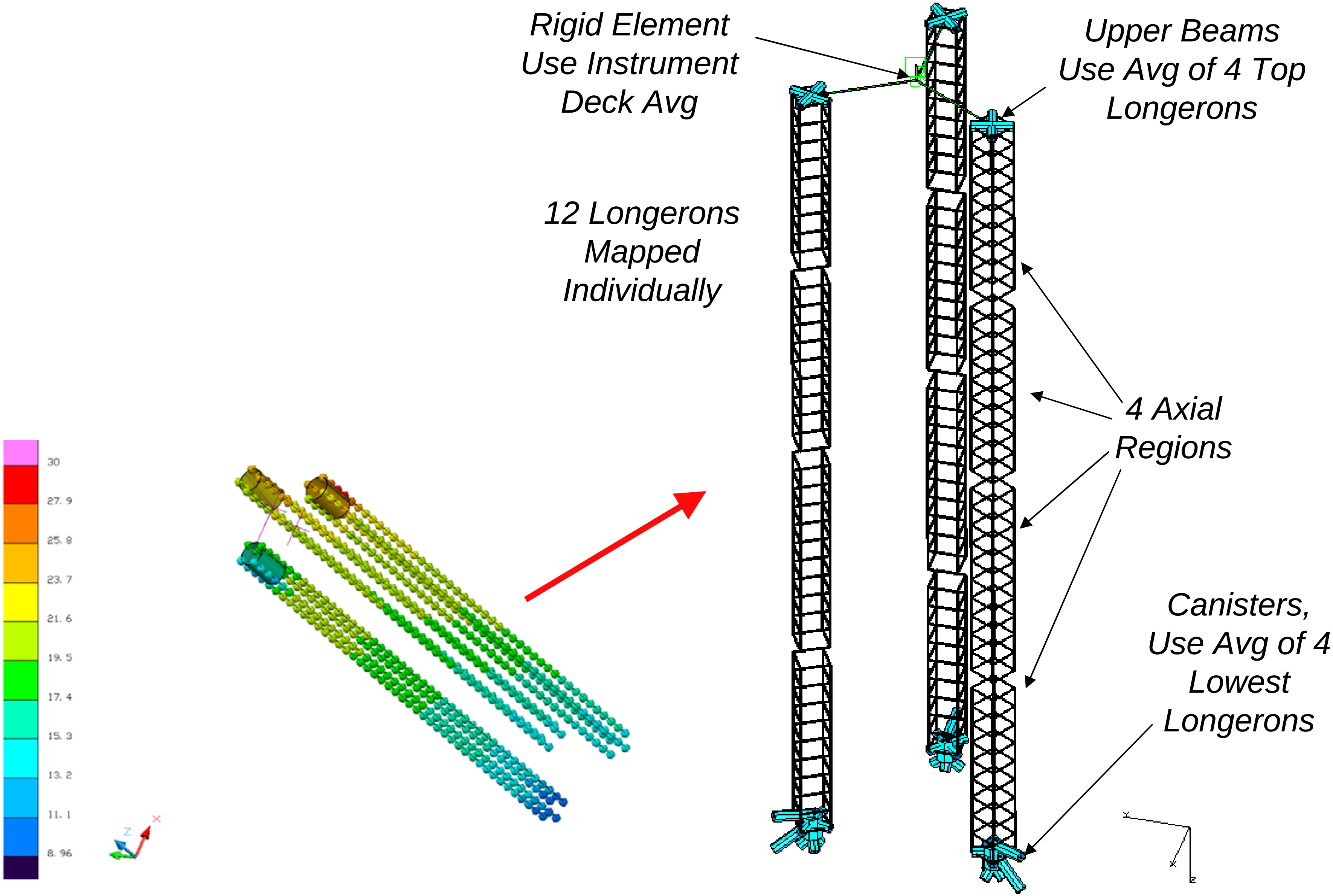
- Resulting attitude excursion about Y axis during burns: 0.165 arcsec; meets IXO pointing requirements

Integrated Thermal Distortion Analysis

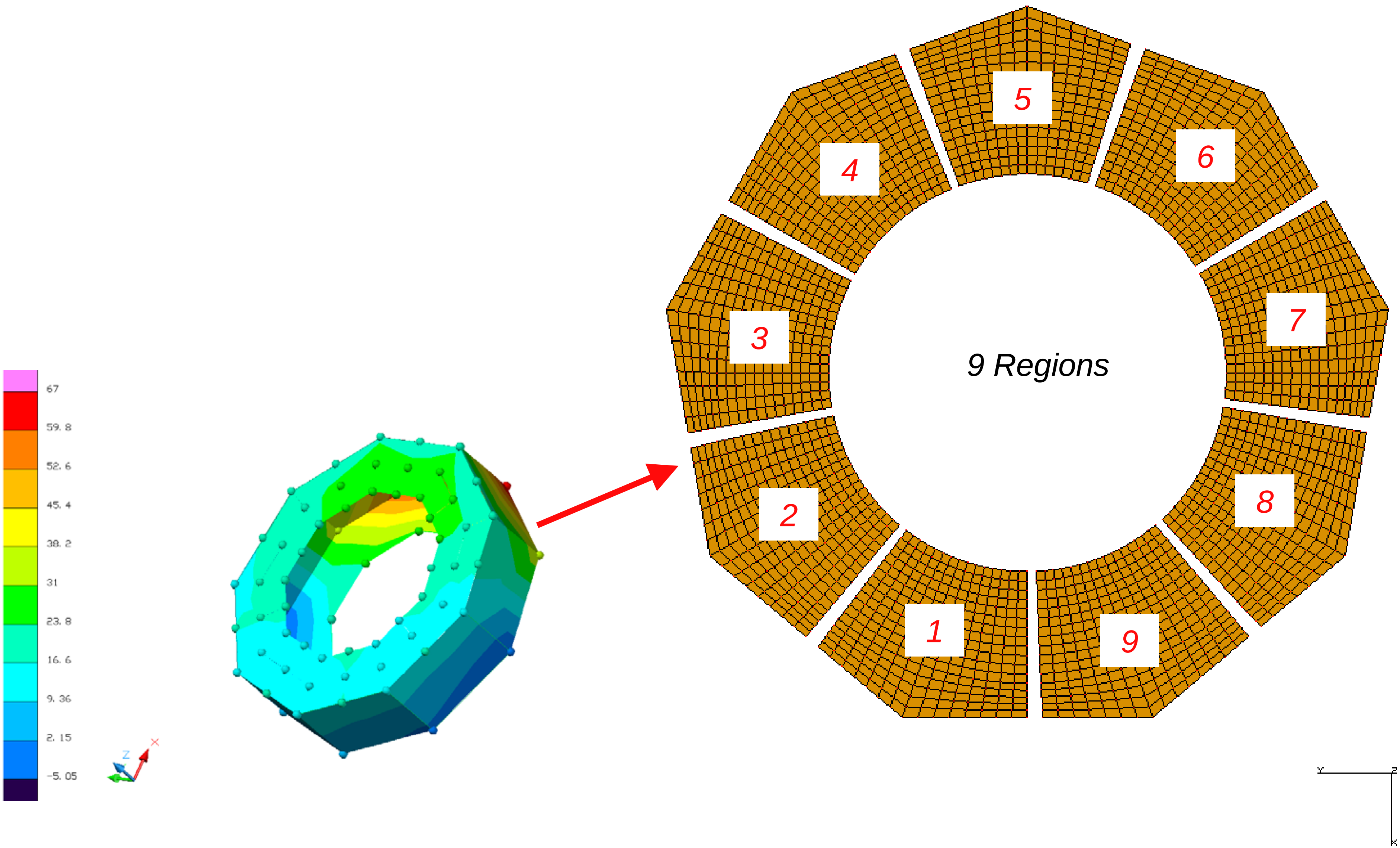
Temperature Mapping

- Temperatures from the thermal analysis model are mapped onto the structural finite element model
- Temperature cases are analyzed for three SV orientations
  - 0 degrees pitch, 0 degrees roll
  - -20 degrees pitch, 20 degrees roll
  - +20 degrees pitch, 20 degrees roll
- Changes in deflection due to slew maneuvers are determined by taking the differences between the three cases

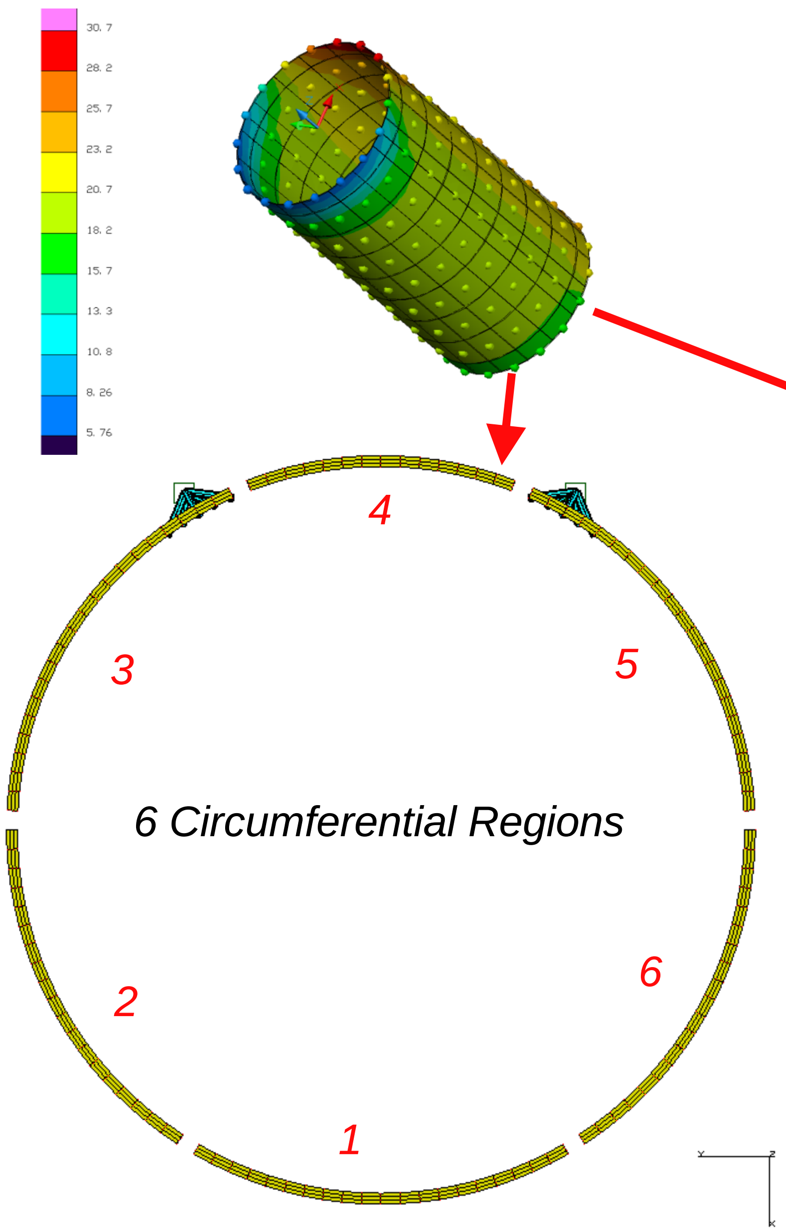
Mast LongeronsTemperature Mapping

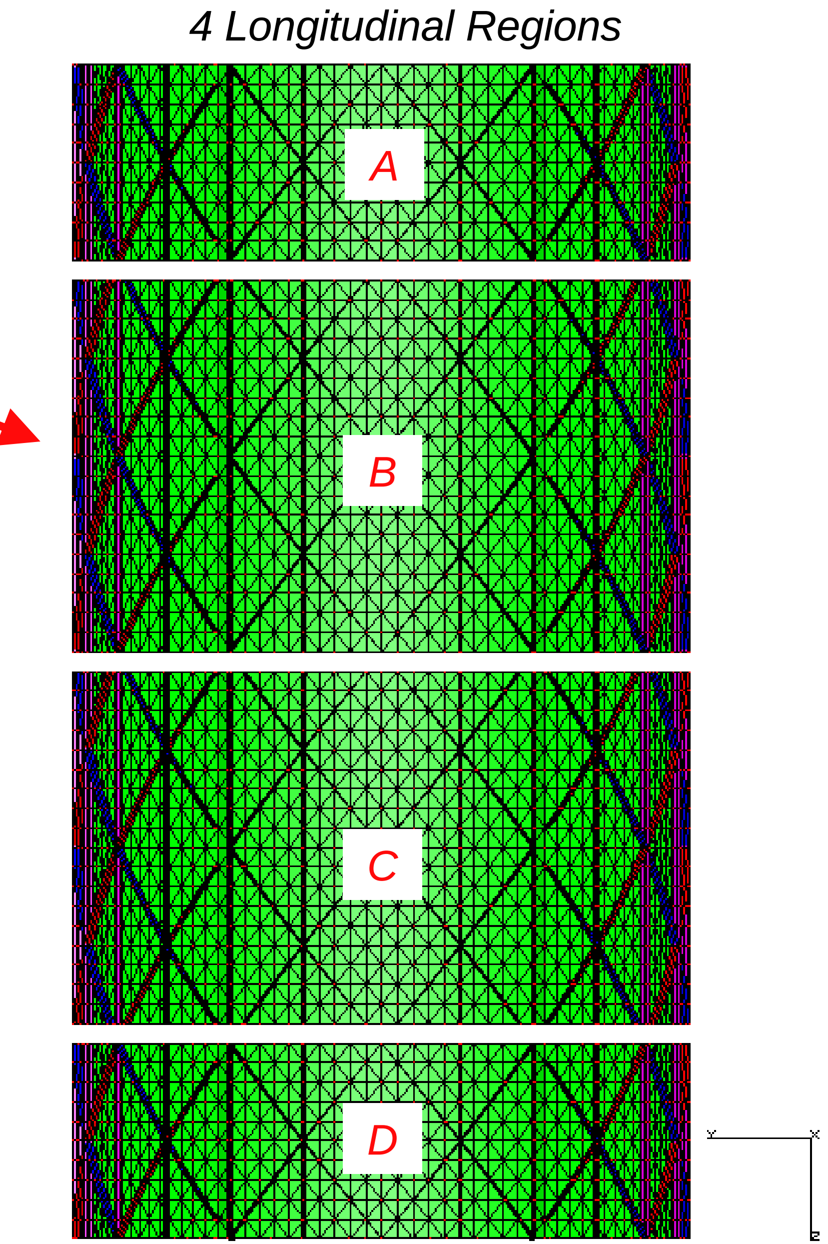


Bus Aft Deck Temperature Mapping

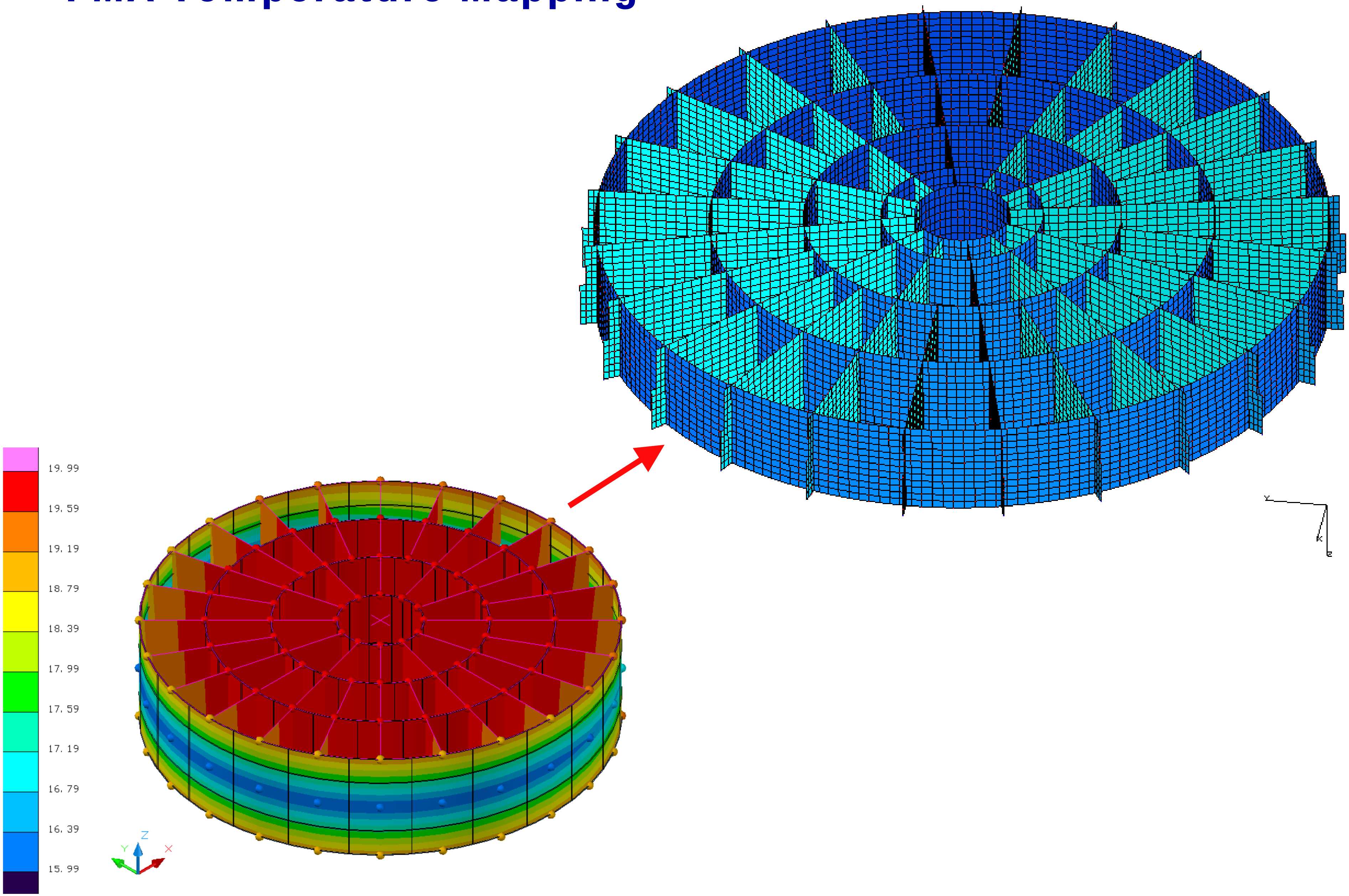


FMS Temperature Mapping





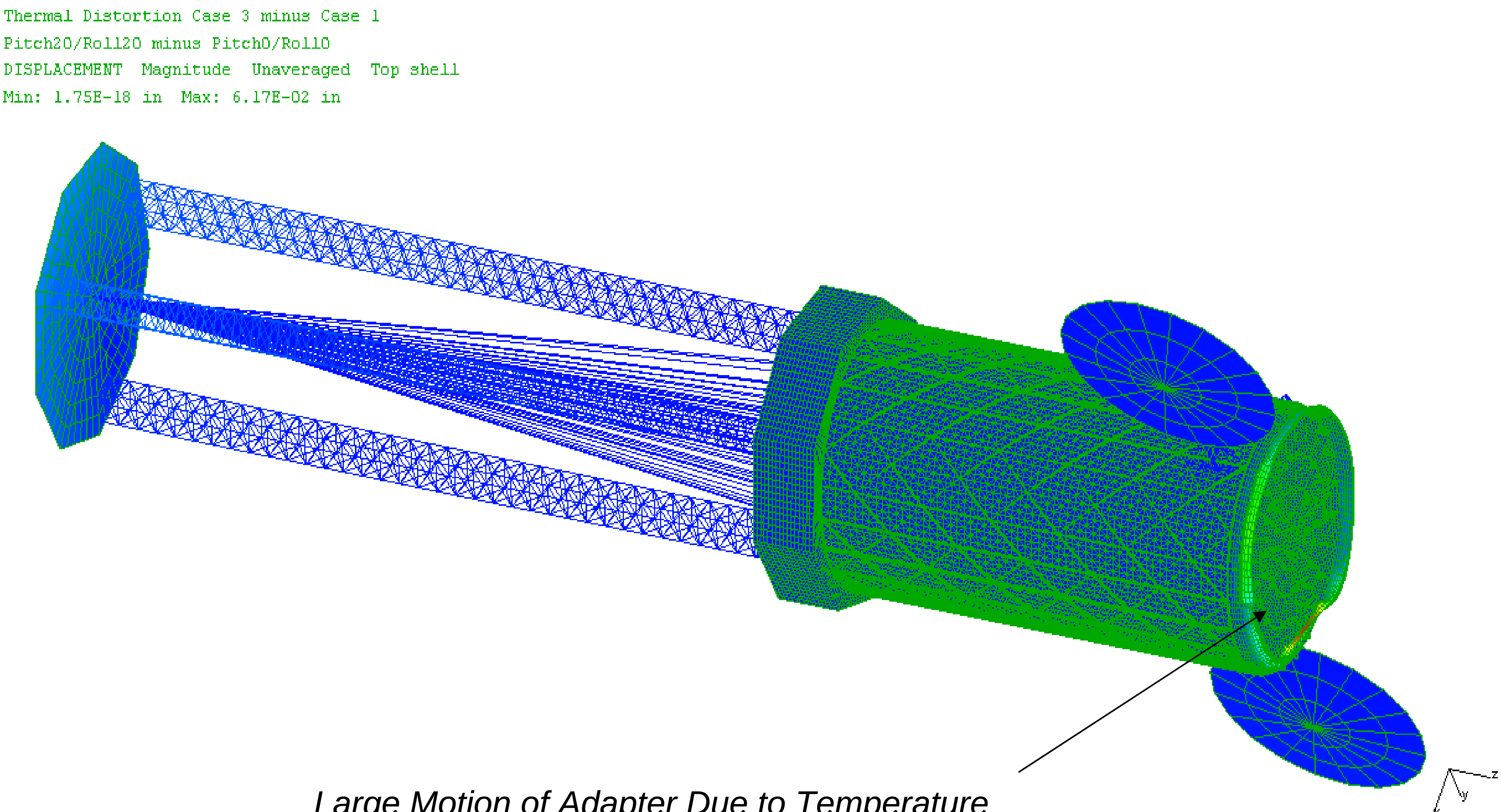
FMA Temperature Mapping



Thermal Distortion Model Configuration

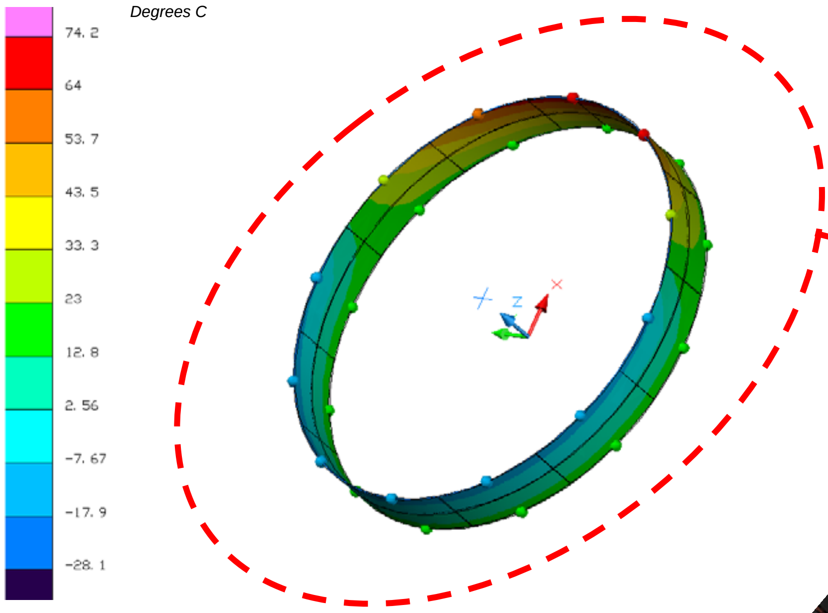
- Model Kinematically Restrained at FMA
- Material Properties (Coef. Of Thermal Expantion, CTE)
  - Aluminum, +22.5E-6 /degC
    - Spacecraft Adapater, Instrument FIP
  - M55J QI, -0.3E-6 /degC
    - FMA, Isogrid
  - M55J QI Facesheet on Aluminum Honeycomb, +0.5E-6 /degC
    - Bus structure
  - ADAM masts, +0.34E-6 /degC (from ATK tests of similar masts)

Slew: Pitch-0 / Roll-0 to Pitch-20 / Roll-20



Large Motion of Adapter Due to Temperature Gradients at Aft End of Adapter
Other Deflections Relatively Small

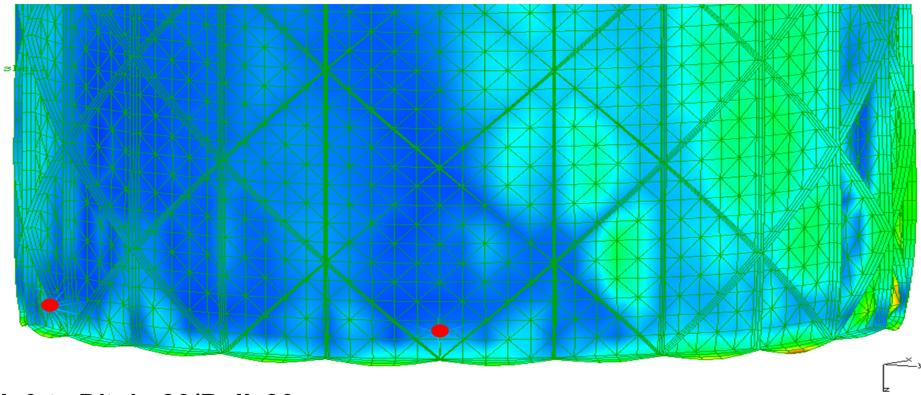
Aluminum Payload Adapter Temperatures



+Z End Has Large Temperature Gradients
-Z End Very Stable Due to Heatpipes

Integrated Thermal Distortion Analysis Result: Temperature Caused Severe Motion of Star Tracker

- Bottom of FMS is "pulled in" by aluminum payload adapter, and that causes rotation of star trackers > 2 arcsec if mounted on isogrid structure



Slew From Pitch_0/Roll_0 to Pitch_20/Roll_20

	DISPLACEMENTS						
LOCATION	POINT ID.	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	20096	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	60857	-0.0001	-0.0002	0.0000	0.003	0.000	-0.015
+Y Star Tracker	60858	0.0036	0.0002	0.0018	1.237	2.688	-0.319
-Y Star Tracker	60864	0.0018	0.0029	0.0022	-1.738	2.312	-0.180
Image on Focal Plane		0.0052	0.0776	-0.0074	1.097	-0.079	0.199

Slew From Pitch_0/Roll_0 to Pitch_-20/Roll_20

	DISPLACEMENTS						
LOCATION	POINT ID.	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	20096	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	60857	-0.0002	-0.0003	0.0000	0.003	0.000	-0.009
+Y Star Tracker	60858	0.0020	0.0015	0.0010	-0.067	1.110	0.086
-Y Star Tracker	60864	0.0001	0.0021	0.0001	-0.335	0.268	-0.308
Image on Focal Plane		0.0027	0.1018	-0.0134	1.314	-0.035	0.245

- Focal Plane Image Deflections Within Acceptable Limits
- Star Tracker Rotations Excessive When Located on Isogrid
- Resolution: Star Trackers moved to center of FMA (see next slide)

Thermal Distortion Conclusion: Requirements Met with Star Tracker Relocated to Center of FMA Inside Shroud

Slew From Pitch_0/Roll_0 to Pitch_20/Roll_20

	DISPLACEMENTS					
LOCATION	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	-0.0001	-0.0002	0.0000	0.003	0.000	-0.015
+Y Star Tracker	0.0000	0.0000	0.0000	0.000	0.000	0.000
-Y Star Tracker	0.0000	0.0000	0.0000	0.000	0.000	0.000
Image on Focal Plane	0.0052	0.0776	-0.0074	1.097	-0.079	0.199

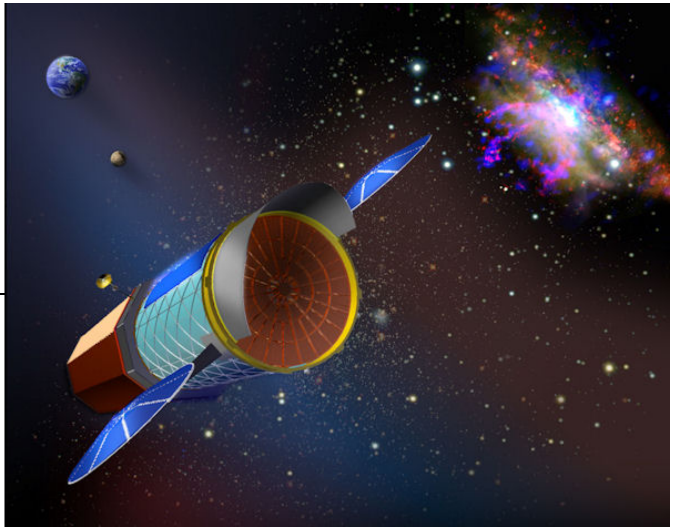
Slew From Pitch_0/Roll_0 to Pitch_-20/Roll_20

	DISPLACEMENTS					
LOCATION	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	-0.0002	-0.0003	0.0000	0.003	0.000	-0.009
+Y Star Tracker	0.0000	0.0000	0.0000	0.000	0.000	0.000
-Y Star Tracker	0.0000	0.0000	0.0000	0.000	0.000	0.000
Image on Focal Plane	0.0027	0.1018	-0.0134	1.314	-0.035	0.245

- After relocation Focal Plane Image Deflections Within Acceptable Limits

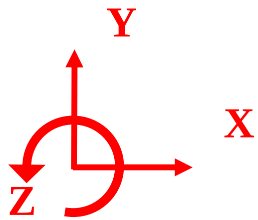
IXO Systems Definition Document
Chapter 5

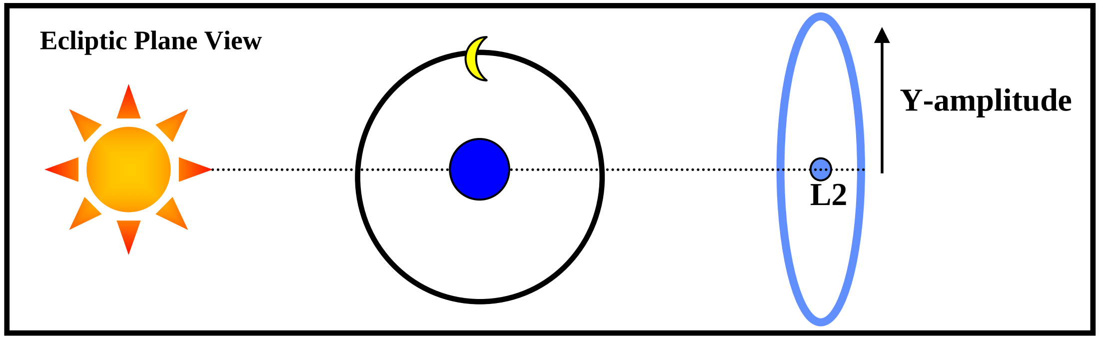
Flight Dynamics



IXO Flight Dynamics Requirements

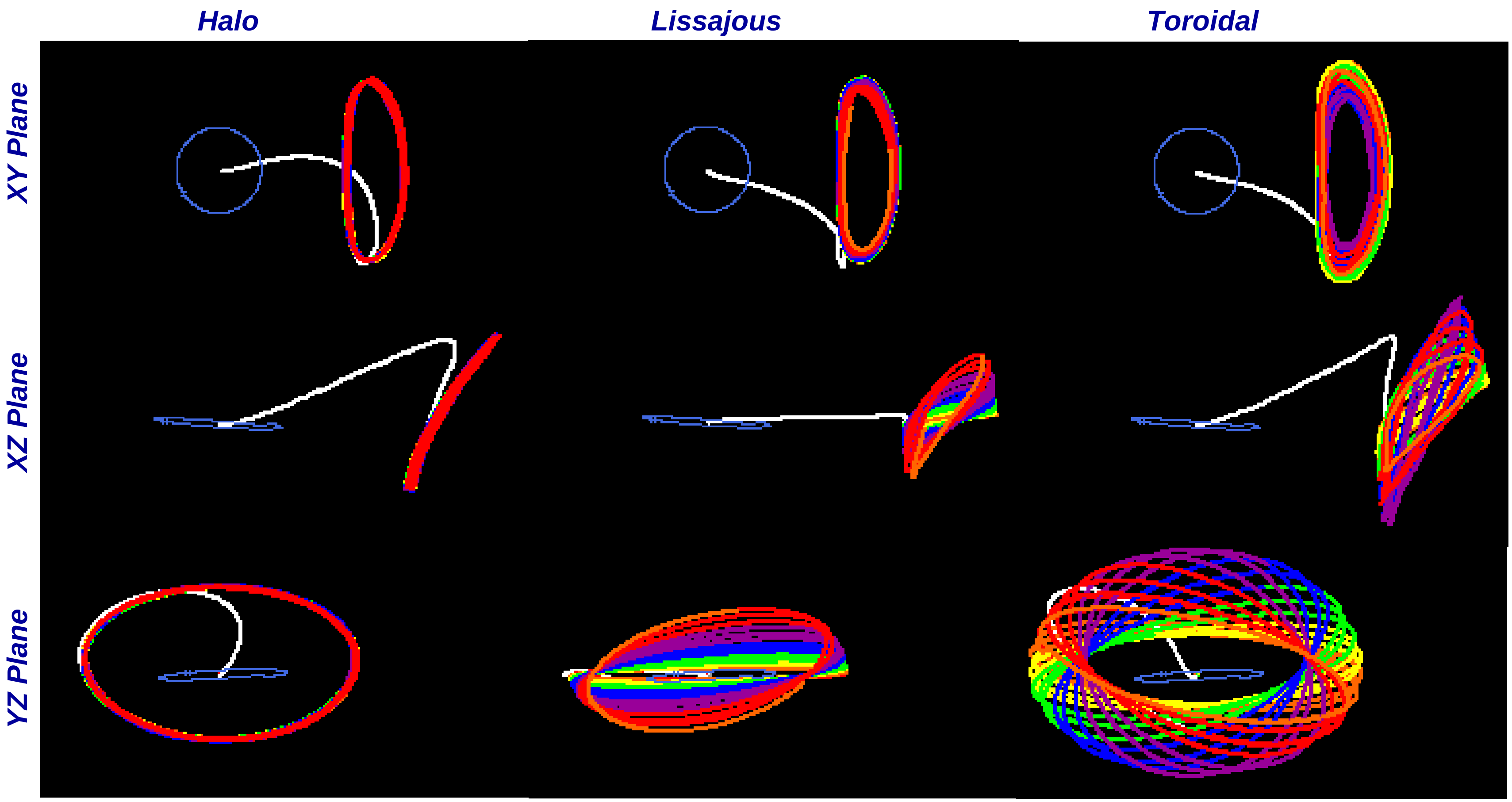
- Launch from the Eastern Range (KSC) on a direct transfer to a Sun-Earth L2 libration point orbit no earlier than December, 2020
- Launch energy: -0.5 km^2/s^2 (upper limit)
- Launch Vehicle: EELV or Ariane 5
- Lifetime: 5 years (10 years consumables)
  - Orbit selected to assure no eclipses and 0 % obscuration (including lunar) at all times during the mission
- L2 Mission Orbit Size:
  - Y Amplitude ≤ 800,000 km (in ecliptic plane perpendicular to Earth-Sun line)
  - Z Amplitude ≤ 500,000 km (out of ecliptic plane)
  - This size is identical to the requirements for JWST and does not require an orbit insertion maneuver upon arrival to the L2 region
  - Size restriction is consistent with IXO viewing requirement and ensures that the Sun does not intrude upon mirror or instrument





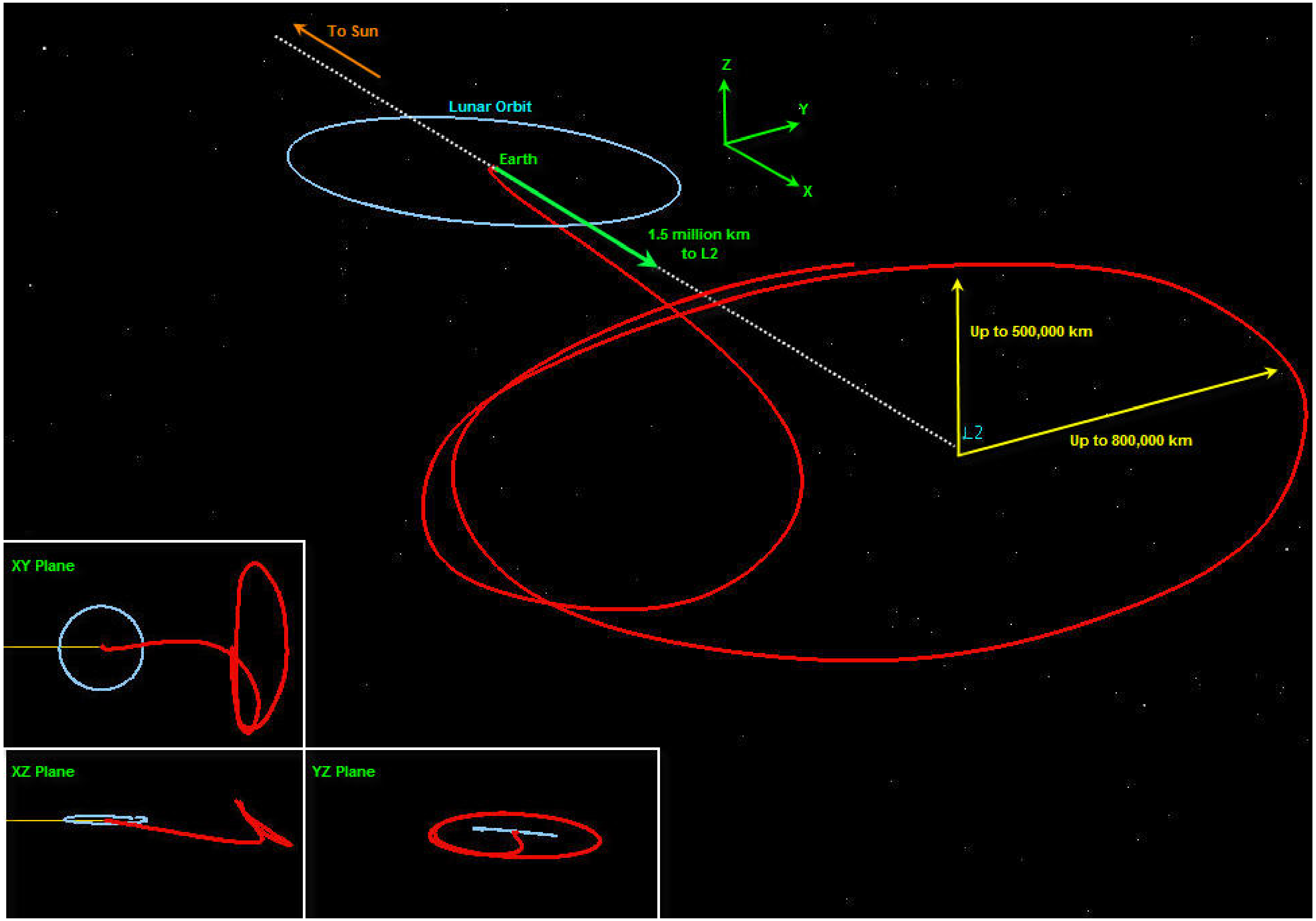
L2 Orbit Possibilities

- There are three distinct orbit types possible (depending on launch parameters)
  - **Halo:** Periodic orbit, in-plane frequency matches out-of-plane frequency (e.g. SoHO)
  - **Lissajous:** Quasi-periodic orbit, path will evolve through the ecliptic plane (e.g. WMAP)
  - **Toroidal:** Quasi-periodic, bounded Lissajous orbit
- Lissajous orbit are most likely to violate the IXO shadow constraint



IXO Orbit Picture

- The picture below shows IXO during the transfer to L2 as well as a single orbit about the Sun-Earth L2 point. The orbit period around L2 is roughly 6 months.



Launch Vehicle – EELV

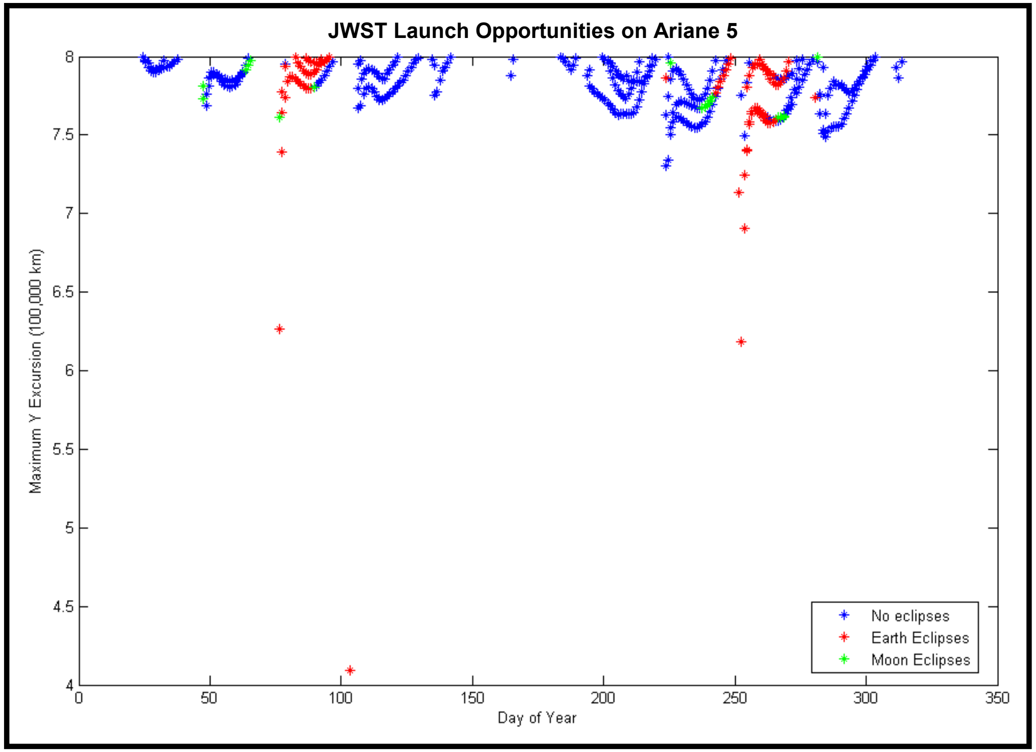
- The EELV flight profile establishes a parking orbit with the first burn of the upper stage
- The time from launch to the parking orbit is roughly 14 minutes
- Historically, the time spent in the parking orbit prior to the second burn (i.e. transfer trajectory insertion) ranges from 10 to 90 minutes
- Battery sizing must accommodate EELV coast capability

Launch Vehicle – Ariane 5

- The Ariane 5 flight profile is a direct ascent from launch until injection into the transfer orbit
  - There is no parking orbit
- The time from launch to injection is roughly 25 minutes
- Flight Dynamics engineers have analyzed the Ariane 5 trajectory and its effects on the launch window in support of JWST

IXO Launch Opportunities

- The number of launch opportunities per year (that meet orbit and eclipse requirements) is a function of the candidate launch vehicle
- Ariane 5
  - Extensive work has been performed in support of JWST
  - The JWST analysis shows roughly 144 days per year that meet the L2 orbit size restrictions while exhibiting zero eclipses during operations (pic below)
- EELV
  - Variable coast option yields more launch opportunities
  - Further analysis is needed to quantify this increase relative to the Ariane 5
  - Restricting the parking orbit coast time due to battery discharge during launch operations could reduce the EELV launch opportunities to the same as for the Ariane 5

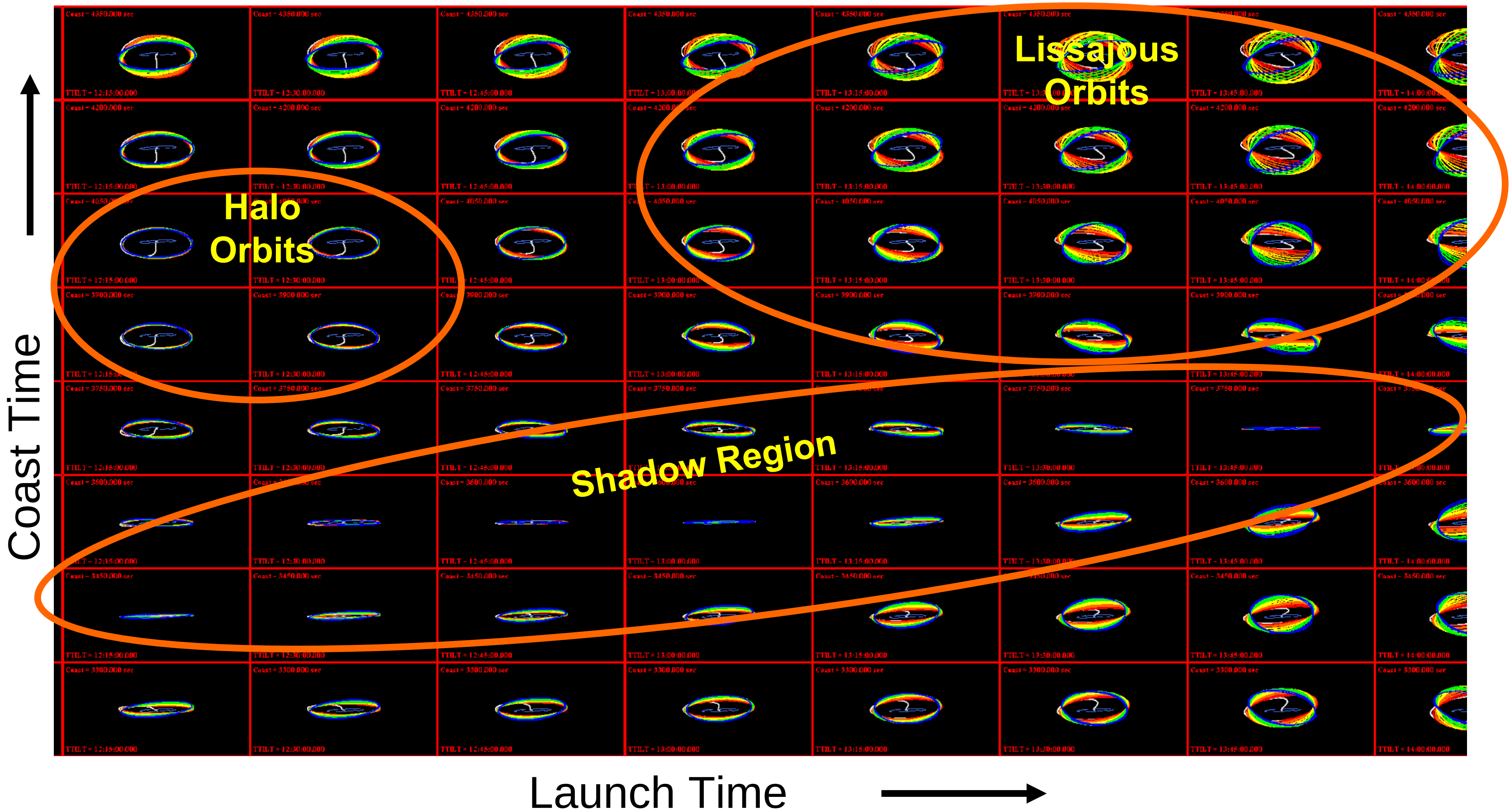


Automated Launch Window Design

- An automated script to map out the L2 orbit solution space for IXO is in process
- The available input launch parameters are
  - Launch Day (EELV and Ariane 5)
  - Launch Time (EELV and Ariane 5)
  - Coast Time (EELV only)
- A mapping of the L2 orbit solution space helps to find the orbit with a Y-amplitude that meets mission constraints
- Further constraint evaluation can filter out cases where shadows occur

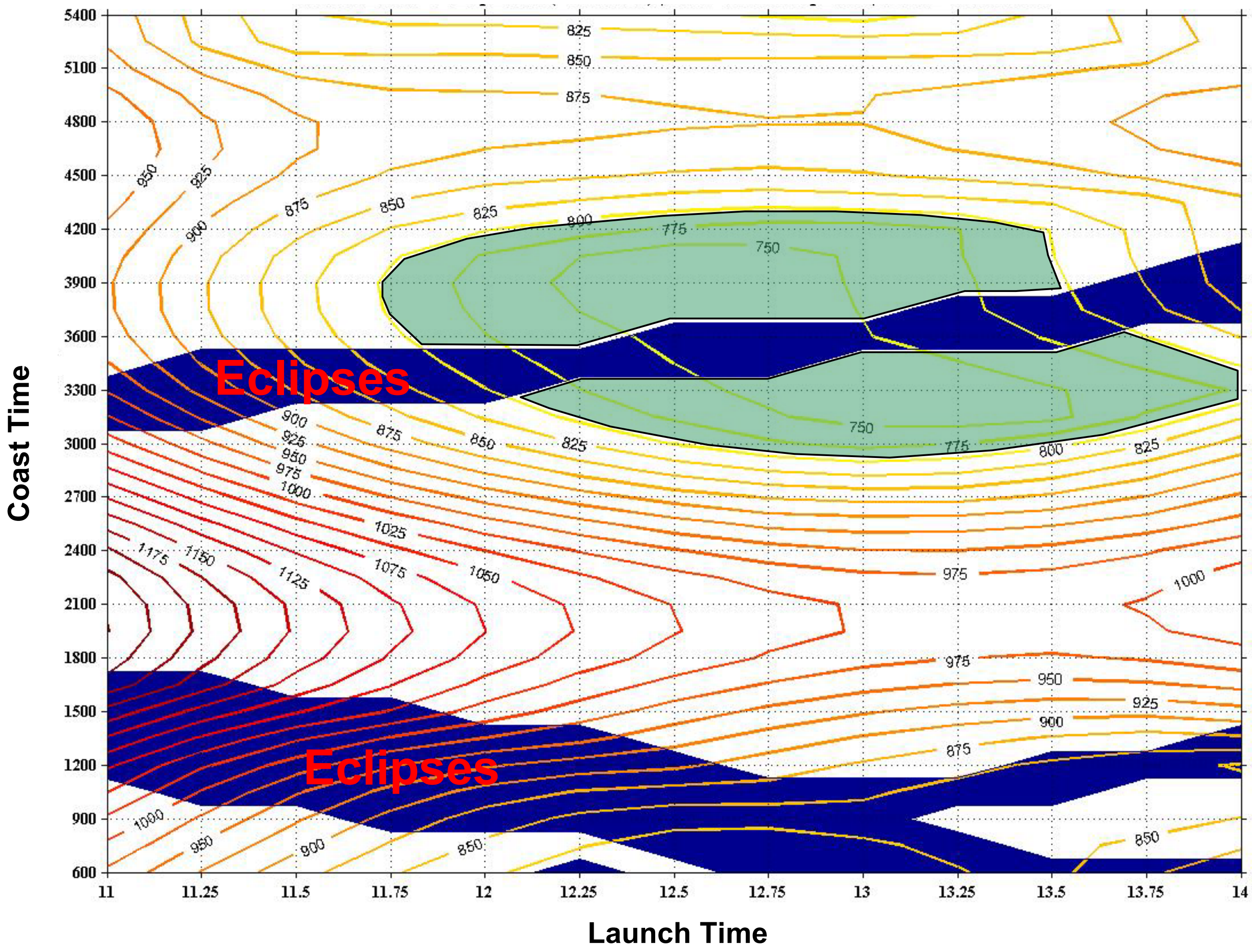
Sample L2 Solution Space

- Sample daily data (for EELV) showing variation in L2 orbits YZ-plane based on changing launch time and parking orbit coast time
- For comparison, the use of the Ariane V limits us to a single horizontal slice through this solution space



Sample L2 Constraint Analysis

- Sample Y-Amplitude contour plot as function of launch and coast times (EELV)
- Regions where eclipses occur are shaded in blue
- Y-Amplitude varies between 735,000 km and 1,250,000 km
- Corresponding Z-Amplitude varies between 17,000 km and 1,070,000 km
- Regions where IXO orbit constraints are satisfied are shaded in green
- Limiting coast time due to battery discharge could remove this day from launch window



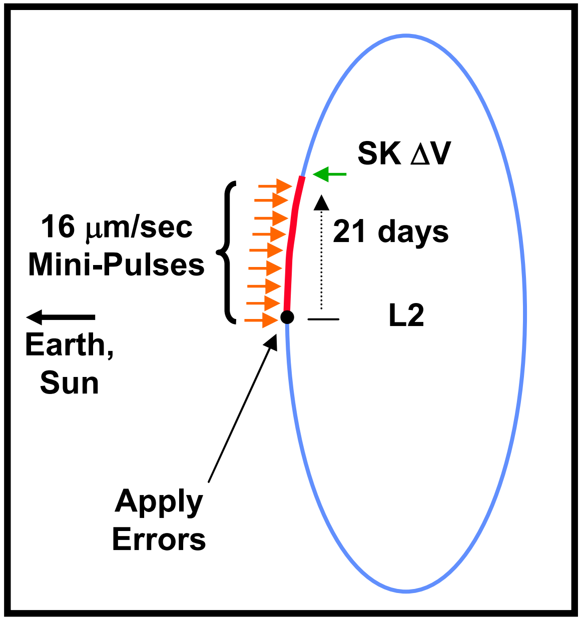
Libration Point Orbit Control

- IXO will be required to perform periodic stationkeeping maneuvers given that any orbit about the Sun-Earth L2 point is unstable due to a buildup of orbit perturbations, the chief of which is solar radiation pressure
- IXO will experience large solar torques due to a large offset between its Center of Pressure (CP) and Center of Gravity (CG)
- The solar torque can be countered in two ways
  - Thrusters are used to continually counter the solar torque
  - As a fallback option, reaction wheels could store the accumulated momentum followed by dumping that momentum via thruster firings (as per JWST and WMAP). Wheel sizing will determine the amount of momentum storage and the frequency of the off-loading.
    - WMAP unloads momentum roughly every 90 days
    - JWST plans to unloads momentum roughly every 3 days
- The current IXO baseline has a thruster firing a mini-pulse every 18 minutes to counter the solar torque (a pure couple to eliminate translational ΔV is difficult to implement in the current observatory design)
- The characteristics of this Mini-Pulse are
  - Thrust: 0.9 N
  - Isp: 220 sec
  - Thrust Time: 0.11 sec
  - Delta-V: 16 micro-meter/s (assuming a 6300 kg spacecraft)
- This continuous Mini-Pulse will affect the stationkeeping in the mission orbit
  - The effect of the Mini-Pulsing is secondary in the transfer orbit

IXO Stationkeeping Analysis

- Because of the frequent Mini-Pulses, IXO will require stationkeeping every 21 days to maintain its orbit around L2
- Stationkeeping analysis assumes certain errors are applied at the beginning of a cycle
  - Orbit Determination (Velocity): 2 cm/s
  - Maneuver Execution: 6 mm/s (5%)
  - Solar Radiation Pressure: 10%
- Applying the errors and accounting for the Mini-Pulses leads to stationkeeping maneuver sizes of about 13 cm/s every 21 days (2.3 m/s per year)
- While this adds up to less than the budgeted 4 m/s per year we are not prepared at this time to reduce that line item at this early stage in the program

L2 Stationkeeping



IXO Delta-v Budget for Atlas-V

- The EELV ΔV budget for IXO
  - Launch Window 10 m/s[1]
  - ELV Dispersion Correction 20 m/s[2]
  - Mid-Course Corrections (2) 10 m/s[3]
  - L2 Stationkeeping (10 years) 40 m/s[4]
  - End of Life Disposal 1 m/s[5]
  - Total 81 m/s
- Assumptions
  1) Accounts for 30 minute finite daily launch window
  2) ELV Dispersion correction assumes EELV dispersions corrected at TTI + 24 hours
     - EELV Dispersion: C3 ±0.05 km^2/s^2 (3σ) [equates to ≈ ±3 m/s at TTI]
     - Accommodates a neutral "mid"-biased launch
     - Dispersion values were obtained from KSC ELV analysts
  3) Two MCC maneuvers to correct for execution errors (5%) on ELV correction maneuver
  4) Budgeting 4 m/s/year
  5) Small maneuver to ensure that observatory leaves the Earth-Moon system

IXO Delta-v Budget for Ariane 5

- The Ariane 5 ΔV budget for IXO

– Launch Window	5 m/s[1]
– ELV Dispersion Correction	21 m/s[2]
– Launch Margin	8 m/s[3]
– Mid-Course Corrections (2)	13 m/s[4]
– L2 Stationkeeping (10 years)	40 m/s[5]
– End of Life Disposal	1 m/s[6]
– Total	88 m/s

- Assumptions
  1) Deterministic maneuver accounts for Ariane performance
  2) Assumes dispersions corrected at TTI + 12 hours [consistent with JWST and Hershel/Planck]
  3) Margin to correct for dispersions at TTI + 18 hours
  4) Two MCC maneuvers to correct for execution errors (5%) on ELV correction maneuver
  5) Budgeting 4 m/s/year
  6) Small maneuver to ensure that observatory leaves the Earth-Moon system

IXO Orbit Determination

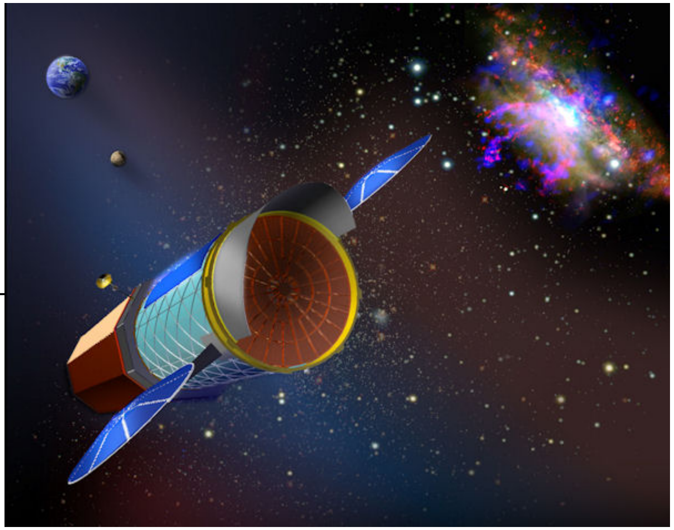
- Orbit Determination (OD) for current Libration point missions (WIND, SoHO, ACE, WMAP) utilizes batch processing
  - Batch processing performs best at L2 in the absence of orbit perturbations (e.g. ΔH maneuvers)
- Frequent ΔH maneuvers seen for JWST has led them to adopt a sequential OD process (i.e. Kalman Filter)
- The sequential OD process does a better job of absorbing the disturbances to the orbit
- Orbit Determination requirements for a comparable Mission (JWST) are:
  - ΔH maneuvers (< 9 mm/s) occur every 3 days
    - All JWST ΔH maneuvers provide translation (no perfect couples). Note: this is not the case for IXO!
  - Stationkeeping maneuvers every 22 days
- IXO decision to employ the Mini-Pulses (16 micro-meter/sec) every 18 minutes to control solar torque forces a similar sequential OD (with Kalman Filter) approach
- Tracking requirements assume two daily 30 minutes range and doppler data form the DSN 34m antenna during cruise (alternating between North & South hemisphere stations), and one daily 30 minutes contact after L2 insertion

NASA\GSFC Libration Point Heritage

- The NASA\GSFC Navigation and Mission Design Branch (Code 595) has the expertise and experience needed in the areas of trajectory design, navigation analysis, and operations for IXO
- Code 595's libration point experience:
  - L1: International Sun-Earth Explorer 3 (ISEE-3) – 1978
  - L1/L2: WIND – 1994 (support is ongoing)
  - L1: Solar and Heliospheric Observatory (SoHO) – 1995 (support is ongoing)
  - L1: Advanced Composition Explorer (ACE) – 1997 (support is ongoing)
  - L2: Wilkinson Microwave Anisotropy Probe (WMAP) - 2001 (support is ongoing)
  - L2: Currently, Code 595 is the lead for trajectory design and navigation for the James Webb Space Telescope (JWST).
- IXO will be very similar in architecture to JWST (e.g. requiring a sequential orbit determination process due to the frequent momentum unloads)
  - Code 595 involvement in IXO will be able to leverage greatly off the experience gained through the current JWST support

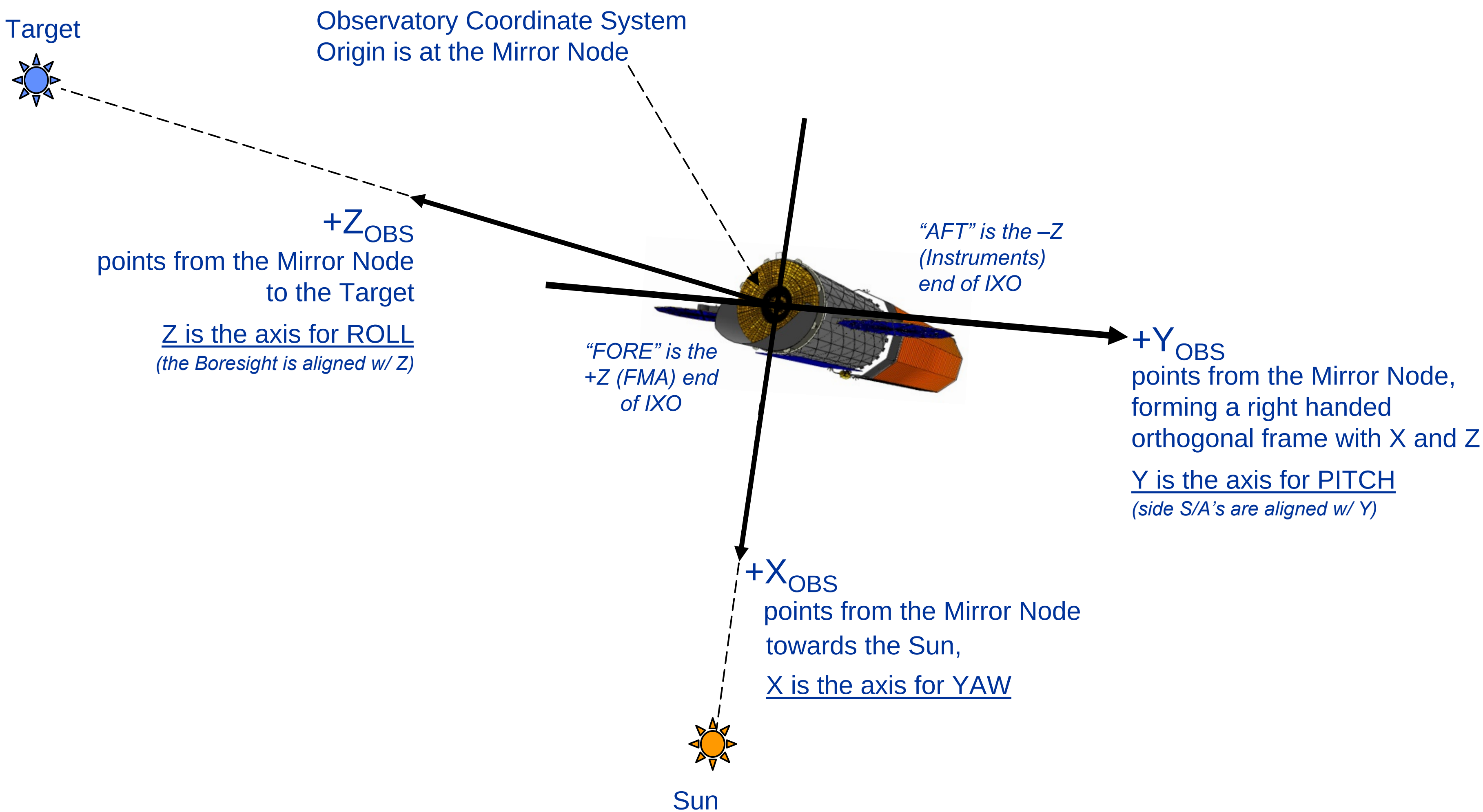
IXO Systems Definition Document
Chapter 6

Pointing and Alignment



Pointing Overview

Observatory Master Coordinate System and Key Terms

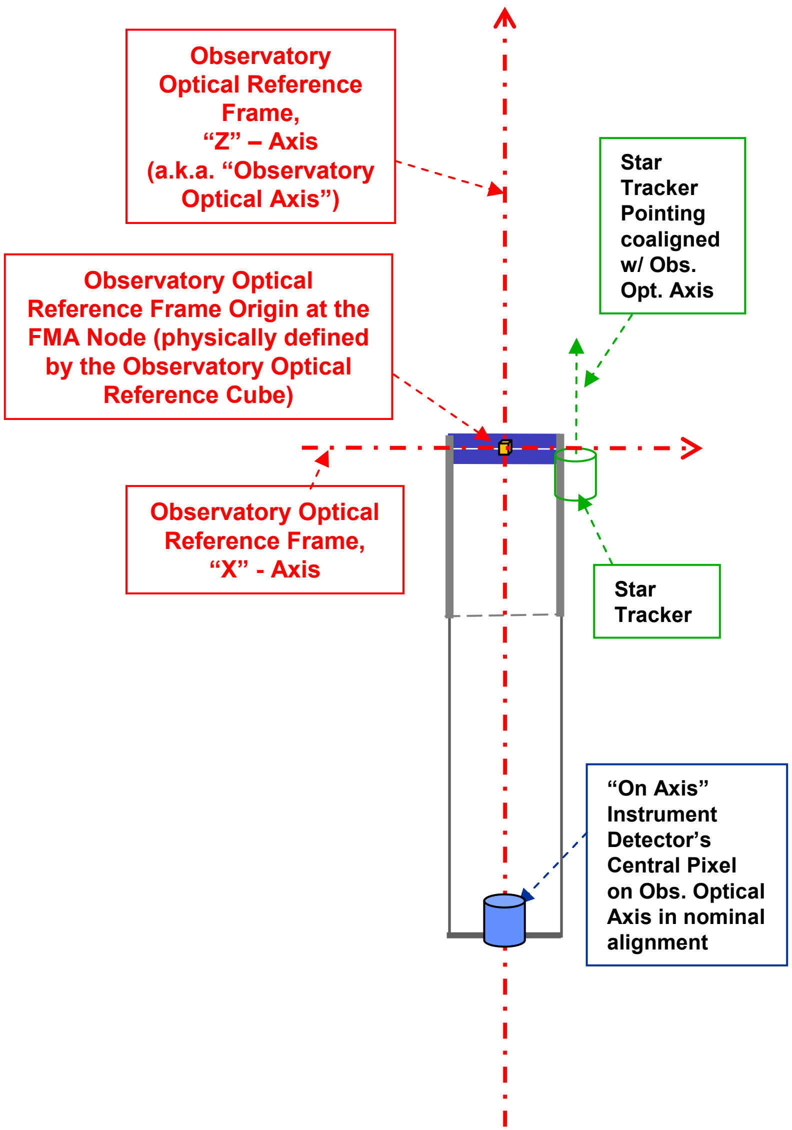


Key Terms Defined:

Spacecraft = Observatory - Science Payload

Observatory Optical Axis, Observatory Optical Reference Frame, and Observatory Optical Reference Cube

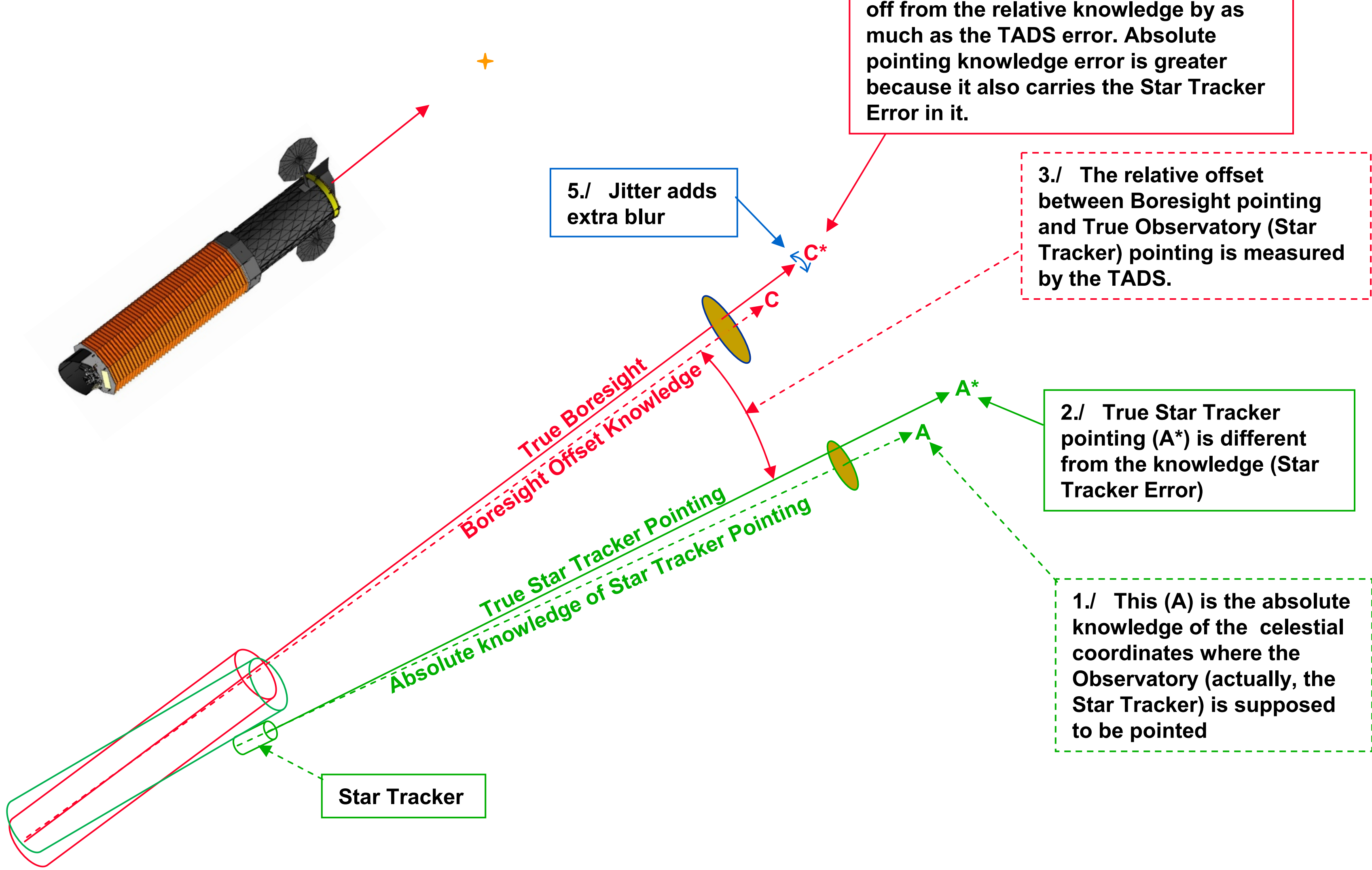
- The Observatory Optical Axis is the theoretical optical centerline of the Observatory
  - The Observatory Optical Axis is the "Z" axis of the Observatory Optical Reference Frame
- The Observatory Optical Reference Frame, in nominal perfect alignment, coincides with the Observatory Master Coordinate System
  - The Origin of the Observatory Optical Reference Frame is at the FMA Node
  - The Star Tracker and the Periscope are both directly aligned to the Observatory Optical Reference Frame; and everything on the Observatory traces its alignment reference to the Observatory Optical Reference Frame
- The Observatory Optical Reference Frame is physically defined by the Observatory Optical Reference Cube
  - The Observatory Optical Reference Cube is judiciously positioned at or near the FMA Node



OBSERVATORY OPTICAL REFERENCE CUBE REQUIREMENT:

- The Observatory Optical Reference Cube reference surfaces shall be no smaller than 5cm on a side
- Errors of the Observatory Optical Reference Cube reference surfaces relative to an ideal cube shall be known after calibration to less than +/- 0.05 arcsec (3σ) at all times

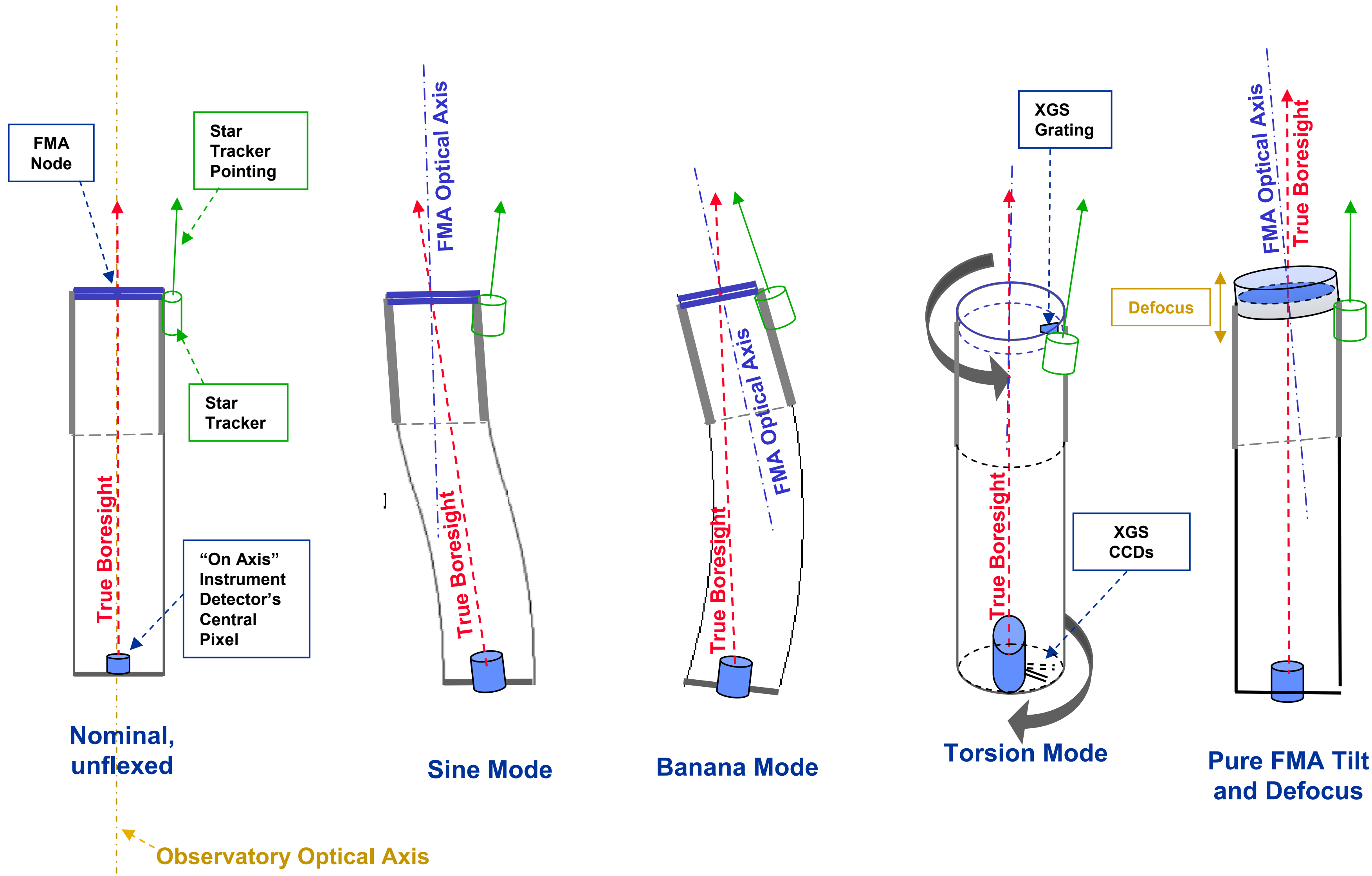
Observatory Level Pointing Basics



True Boresight is defined as the line connecting the center of the "Central Pixel" of the On-axis Instrument (e.g. XMS) to the FMA node.

Flex Body Effects and Structural Misalignments

Boresight to Star Tracker and Boresight to FMA Optical Axis

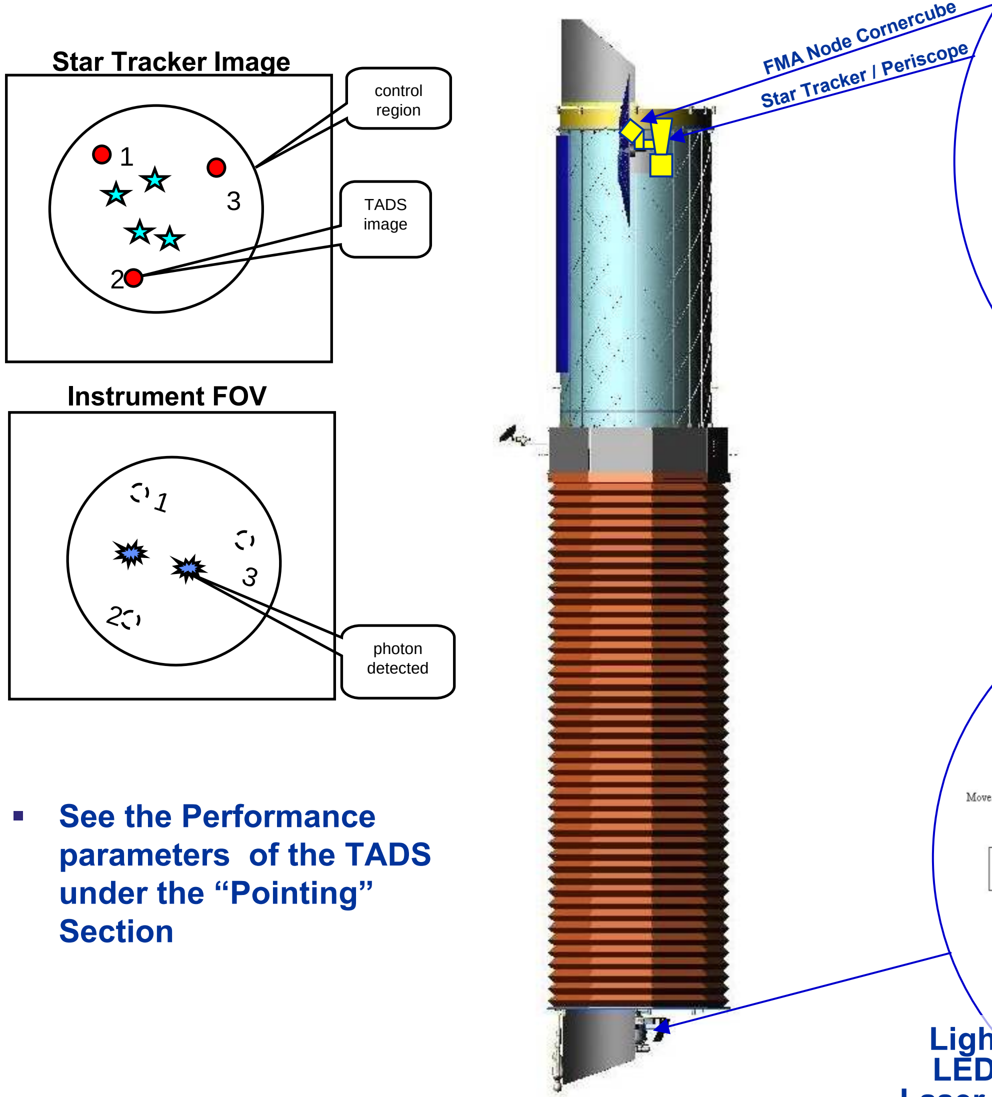


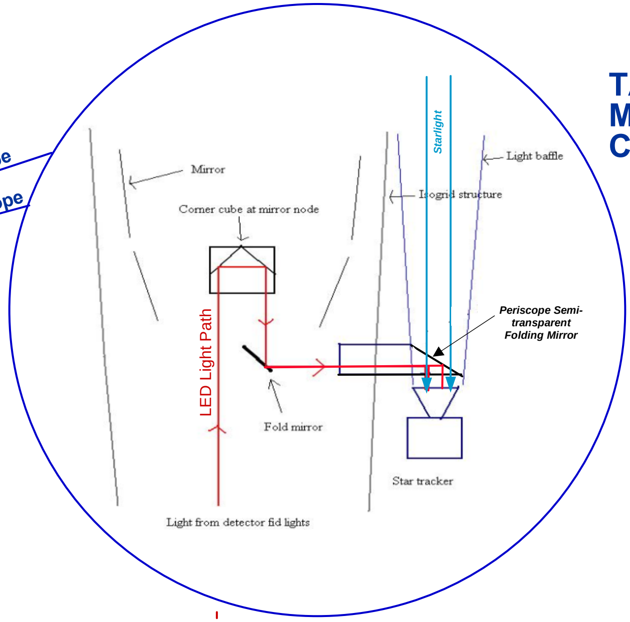
Spitzer's AST-301 Star Tracker (by LMATC)

- Accuracy
  - 0.15 as (1σ), or .25 as [HPD]   X and Y axes*
    - ** After in flight optical distortion calibrations*
  - 6.0 as (1σ)   Z axis
    - *Before in flight optical distortion calibration*
- Detector / FOV
  - FOV is 5-by-5 degree
  - Clearance 3.54 degree ½ cone angle
  - 512 x 512 pixels
  - Pixel size: 15 x 15 micrometer = 35 x 35 as
- NEA
  - 0.11 arcsec* (1σ) about X and Y axes, 3.1 arcsec about Z axis
    - ** after in flight optical distortion calibrations*
  - Bias error is 0.15 about X and Y axes, 4.0 arcsec about Z axis (1σ)
  - Centroiding to 1/100 of a pixel
- Senses 9.2 magnitude start (~50 stars)
  - Responds to 450-850 nm
- Guide Star Compensation for
  - Proper motion
  - Parallax
  - Velocity aberration and optical distortion
- Output quaternion at 2 Hz rate, Operable (at reduced accuracy) at up to 2.1 deg/s
- Acquisition time: 3 seconds
- Mass: 7.1 kg per unit; Power: 18 W per unit; Dimensions: 30.2 cm (L) x 13.3 cm (H) x 15.3 cm (W)
- 1553 bus
- Heritage: Spitzer

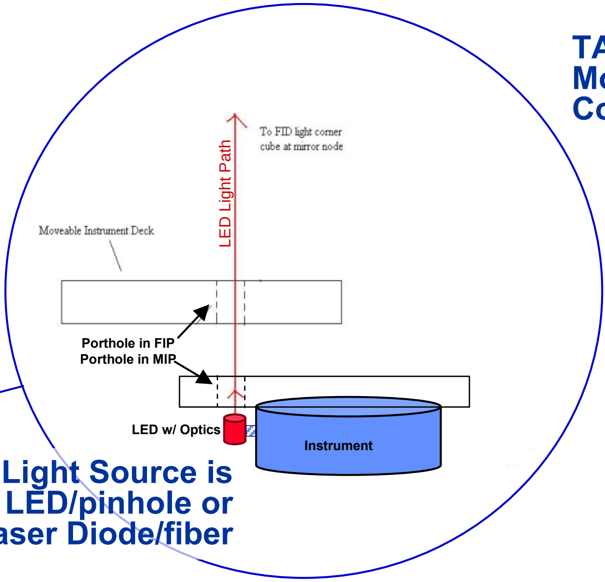
Source: SIRTF Autonomous Star Tracker (SPIE Paper 4850-12),   Roel van Bezooijen

Telescope Aspect Determination System (TADS)





TADS Optics Module Components

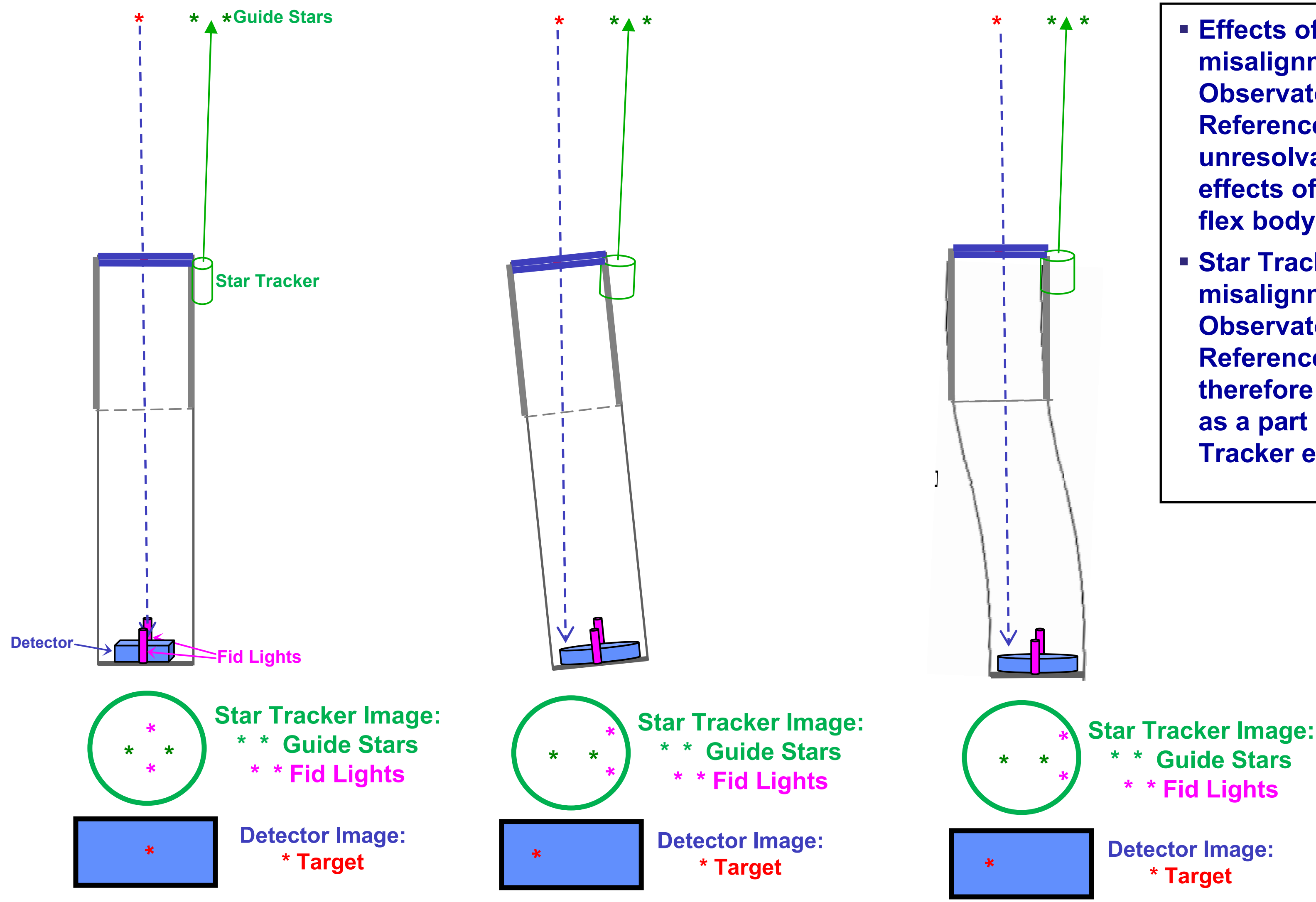


TADS Instrument Module Components

Light Source is LED/pinhole or Laser Diode/fiber

- See the Performance parameters of the TADS under the "Pointing" Section

Star Tracker Misalignment Confusion w/ Observatory Flex Body Misalignment



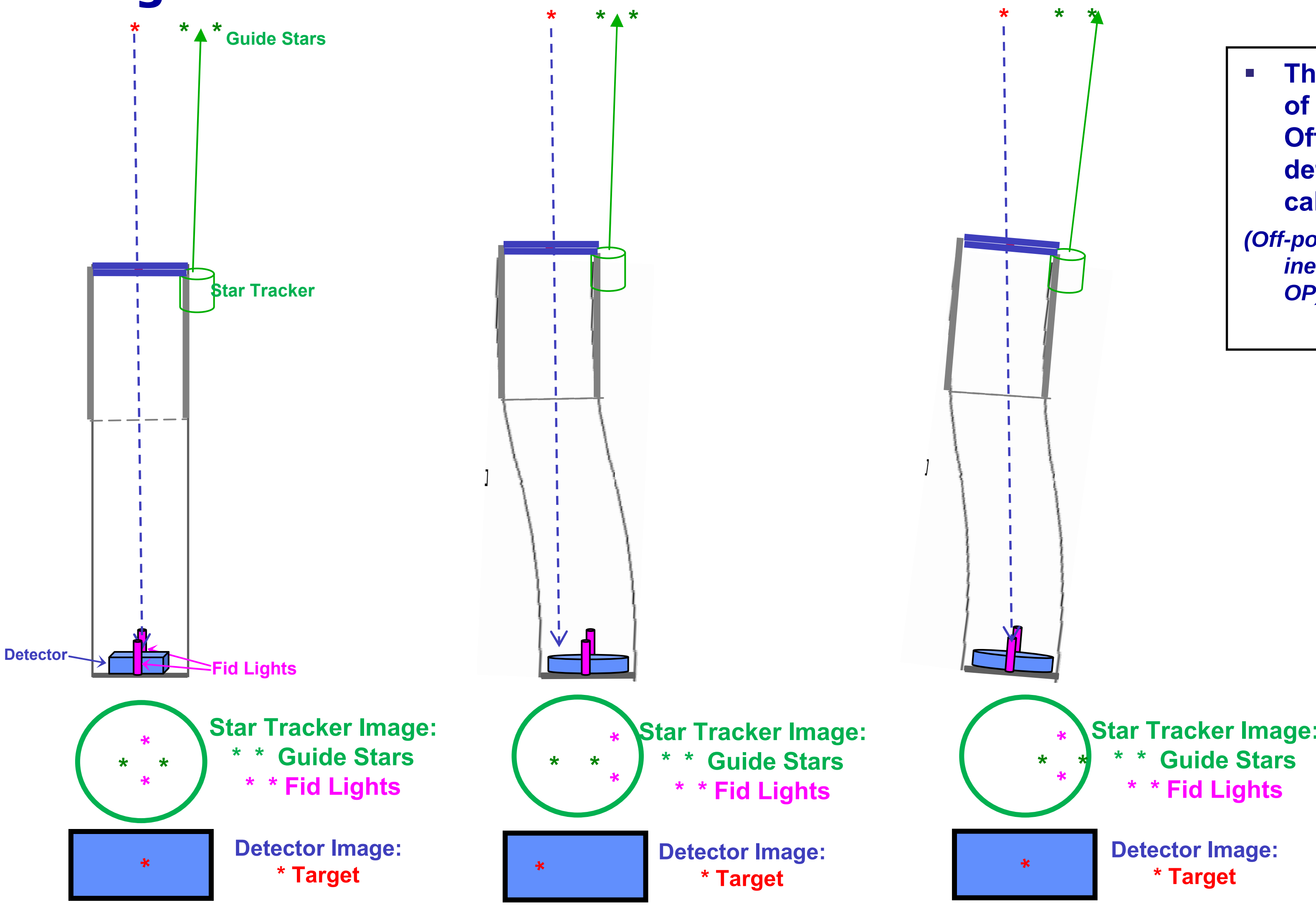
Nominal Alignment

Star Tracker Misalignment

Observatory Flex Body Misalignment

- Effects of Star Tracker misalignment relative to Observatory Optical Reference Frame are unresolvable from effects of Observatory flex body misalignment
- Star Tracker misalignment relative to Observatory Optical Reference Frame must therefore be budgeted as a part of the Star Tracker end to end error

Observatory Off-pointing Nulls Observatory Flex Body Misalignment



- **The magnitude of Observatory Off-pointing is determined by calibration**

(Off-pointing is ineffective for XGS OP)

Nominal Alignment

With nominal Observatory Pointing, image would be displaced due to Flex Body Misalignment

Observatory Off-pointing cancels effects of Misalignment for on-axis instruments

Forward (Rigid Body) Pointing Knowledge

Rigid Body Pointing Requirements and Star Tracker End-to-End Expected Performance

FORWARD POINTING REQUIREMENT:

- **0.6 arcsec radial (3σ)**
  - Flowed down from 1 arcsec (3σ) Image Position Reconstruction Knowledge (a.k.a.: "Aspect Reconstruction") Requirement:

STAR TRACKER END-TO-END EXPECTED PERFORMANCE:

- **0.18 arcsec (1σ)** *(or 0.30 arcsec [HPD])*, **or 0.54 arcsec (3σ)**
  - That is the RSS of:
    - 0.15 as (1σ) for star tracker error, and
    - 0.10 as (1σ) for star tracker/ Periscope Assembly - to - Observatory Optical Reference Frame alignment error

Rear (Flex Body) Pointing Knowledge
TADS Requirements and Expected Performance

REAR POINTING REQUIREMENT (Metering Structure flex body deflection knowledge):

- **0.25 arcsec (1σ)** *(or 0.75 arcsec [HPD])*, **or 0.75 arcsec (3σ) in X and Y**
  - *As flowed down from 1 arcsec (3σ) Image Position Reconstruction Knowledge (a.k.a.: "Aspect Reconstruction") Requirement*

TADS EXPECTED PERFORMANCE

- **Metering Structure flex body deflection knowledge expected:**
  - **0.23 arcsec (1σ),** *(or .39 arcsec [HPD])*, **or 0.70 arcsec (3σ) in X and Y**
    - That is the RSS of:
      - 0.15 as (1σ) for star tracker error (evaluating FID lights), and
      - 0.18 as (1σ) Periscope end-to-end performance
- **Relative Position Knowledge Of Two Fid Lights expected (i.e. CCD Camera distance from XMS):**
  - **0.18 arcsec (18 microns) (1σ) in X and Y**
    - That is the RSS of two Star Tracker NEA's at .11 arcsec ea.
- **Periscope To Star Tracker Coalignment**
  - **1.0 as (1σ) with 0.05 as (1σ) on orbit variation in X and Y**
- **Dynamic Range: +/- 100 arcsec in X and Y; +/- 20 arcmin in Torsion**

- *TADS design based on Chandra heritage*

Observatory Level Pointing Performance Summary

(Error Budgets and Calculations on following slides)

Term	Definition	Requirement	Predicted Performance	Stat
Image Position Reconstruction Knowledge (a.k.a.: "Aspect Reconstruction")	The absolute knowledge of an image's position relative to the Truth:	• Radial: 1 arcsec (that is Pitch and Yaw combined, equivalent to ~0.7" pitch and ~0.7" roll) • Roll: 30 arcsec	• Radial: .88 arcsec (that is .49 arcsec [HPD]) •Roll: 18 arcsec	3σ
Image Position Control (w/o Translation Mechanism correction)	The absolute precision of placing and keeping an image on the Focal Plane Detector	• Pitch and Yaw: 12 arcsec • Roll: 60 arcsec	• On-Axis Instr's: 1.13 arcsec • XGS: 7.5 arcsec • Roll: 30 arcsec	3σ
Defocus (w/o Focus Mechanism correction)	Abs. max. FMA Node to Detector distance variation without correction by any focus mechanism	• On Axis Inst's: +/- 0.3 mm • XGS: +/- 0.5 mm	• On-Axis Instr's: +/-0.06 mm • XGS: +/- 0.075 mm	3σ
Jitter (excluded from the Image Position Knowledge requirements)	Jitter effects encompass all high frequency errors above the bandwidth of the Control System and Monitoring System	▪ 200 milliarcsec over 200 msec	▪ 20 milliarcsec abs. worst case over any period msec By Reaction Wheel momentum management in a 5 RW configuration, a steady state jitter of < 2 milliarcsec is achievable	HPD

• One mm corresponds to ~10" (or 1 " to 100 um) at 20m

All numbers shown above reflect the natural pointing/alignment performance of the deployed IXO Structure, and exclude any effects of Focus or Translation Mechanisms

- A number of Focus and Translation Mechanisms are used on IXO. With their help , significant improvements in "Predicted Performance" over the numbers shown are achievable.
- In addition, these mechanisms provide assurance against potential errors in misalignment predictions

Motion of Images

Displacement of Images at the Detectors due to Observatory Rigid Body (Tilt) and Flex Body (Translations and Torsion) Effects

Lateral displacement of the FIP relative to the X-ray Beam will cause the image on the Detectors to move (in the coordinate frame of the Detector) in the following manner:

1. For On-Axis Instruments, displacement of the FIP in any direction will cause the image on the Detector to move an equivalent amount in the opposite direction (in the coordinate frame of the Detector)
   – Example: a 1 mm movement of the FIP in the +Y direction will cause the image on the Detector to move 1 mm in the –Y direction (relative to the Detector frame)
2. For CAT Gratings' CCDs, lateral displacement in the Dispersion direction (~X) will cause the image on the Detector to move approximately an equivalent amount in the opposite direction (in the coordinate frame of the CCD)
   – Example: a 1 mm movement of the FIP in the +X direction will cause the image on the Detector to move ~1 mm in the –X direction (relative to the CCD frame)
3. For CAT Gratings' CCDs, lateral displacement in the Cross-dispersion direction (~Y) will cause the image on the Detector to move an equivalent amount in the opposite direction (in the coordinate frame of the CCD)
   – Example: a 1 mm movement of the FIP in the +Y direction will cause the image on the Detector to move 1 mm in the –Y direction (relative to the CCD frame)
4. For OP Gratings' CCDs, lateral displacement in the Dispersion direction (Y) will cause the image on the Detector to move approximately an equivalent amount in the opposite direction (in the coordinate frame of the CCD)
   – Example: a 1 mm movement of the FIP in the +Y direction will cause the image on the Detector to move ~1 mm in the –Y direction (relative to the CCD frame)
5. For OP Gratings' CCDs, lateral displacement in the Cross-dispersion direction (X) will cause the image on the Detector to move, due to the reflection off the grating "mirror", an equivalent amount in the same (!) direction (in the coordinate frame of the CCD)
   – Example: a 1 mm movement of the FIP in the +X direction will cause the image on the Detector to move 1 mm in the +X direction (relative to the CCD frame)

Requirements

Observatory Level Image Position Knowledge (a.k.a. Aspect Reconstruction) Requirement

IXO shall provide knowledge of an image's absolute position, relative to the Truth, to :

1 arcsec radial [3σ] in X and Y, and

30 arcsec [3σ] in Roll

This requirement can be met after post-facto processing

Requirement directly imposed by the IXO Science Definition Team

Observatory Level Image Placement Requirement

Evaluating various Image Placement Requirements as specified by the IXO instruments, the tightest Instrument Level Image Placement Requirement (WFI/HXI and XMS) defines the Observatory Level Image Placement Requirement:

IXO shall place all images on the Detectors with a 12 arcsec (3σ) accuracy

Instrument Pointing Requirements (all values are 3σ)

WFI/HXI	Pointing requirements (knowledge - diameter) (Pitch&Yaw)	1.7	arcsec
	Pointing requirements (control - diameter) (Pitch&Yaw)	12	arcsec
	Pointing requirements (stability - diameter) (Pitch&Yaw)	3.4	arcsec/sec
XMS	Pointing requirements (knowledge - diameter) (Pitch&Yaw)	3.4	arcsec
	Pointing requirements (control - diameter) (Pitch&Yaw)	12	arcsec
	Pointing requirements (stability - diameter) (Pitch&Yaw)	3.4	arcsec/sec
XGS CAT	Pointing requirements (knowledge - diameter) (Pitch&Yaw)	3.4	arcsec
	Pointing requirements (control - diameter) (Pitch&Yaw)	16	arcsec
	Pointing requirements (stability - diameter) (Pitch&Yaw)	3.4	arcsec/sec
XPOL	Pointing requirements (knowledge - diameter) (Pitch&Yaw)	4	arcsec
	Pointing requirements (control - diameter) (Pitch&Yaw)	14.4	arcsec
	Pointing requirements (stability - diameter) (Pitch&Yaw)	4	arcsec/sec
HTRS	Pointing requirements (knowledge - diameter) (Pitch&Yaw)	60	arcsec
	Pointing requirements (control - diameter) (Pitch&Yaw)	60	arcsec
	Pointing requirements (stability - diameter) (Pitch&Yaw)	14.3	arcsec/sec

Pointing knowledge and control values after ground processing of data using the Telescope Aspect Determination System (TADS).

- Such a system (called PCADS) is being used successfully on-board the Chandra X-ray Observatory, and has achieved equivalent pointing stability ~ 6 times better than required for IXO (reference: T. Aldcroft, et al., SPIE Proc. vol 4012, p. 650, 2000) and pointing knowledge ~ 1.7 times better than required for IXO (ref. M. Weisskopf, et al, astroph/0503319v1 2005).
- The use of the TADS eliminates the need to place stringent knowledge and stability requirements on either the instruments or the spacecraft, thereby simplifying instrument and spacecraft implementation and reducing cost.

HEW, HPD vs. σ for 1D and 2D Gaussian distributions

- For a 1D Gaussian distribution, the half energy width (HEW) corresponds to 1.35σ.
- For a 2D Gaussian distribution, the half power diameter (HPD) corresponds to 1.664 σ, where σ is the radial standard deviation.
  - A parameter expressed as x in [1σ] can also be expressed as 1.664*x in [HPD]
  - A parameter expressed as x in [HPD] can also be expressed as 0.6*x in [1σ] , or as 1.8*x in [3σ]
  - A parameter expressed as x in [3σ] can also be expressed as 0.55*x in [HPD]

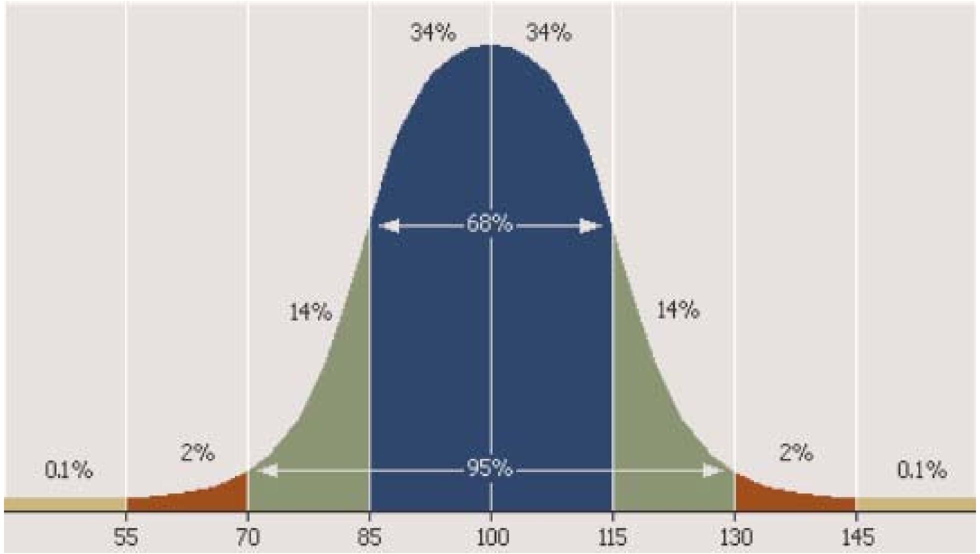


Figure 10. 1D Gaussian Distribution Curve

Pointing Error Budgets

Observatory Level Pointing Knowledge Budget

Image Reconstruction Boresight Pointing Radial Knowledge

Radial Requirement	Expected Performance
1 arcsec radial (3σ)	.88 arcsec radial (3σ)

RSS

Rear Knowledge Error (i.e. TADS Error)

Sub-allocated Requirement	Expected Performance
.75 arcsec radial (3σ)	.70 arcsec radial (3σ)

Forward Knowledge Error (i.e. Star Tracker E-E Knowledge)

Sub-allocated Requirement	Expected Performance
.6 arcsec radial (3σ)	.54 arcsec radial (3σ)

Jitter (outside of TADS bandwidth)

Sub-allocated Requirement	Predicted Performance
.36 arcsec radial (3σ)	.036arcsec radial (3σ)

The Requirement for Roll Knowledge is:
- 30 arcsec (3σ)

The Expected Performance for Roll Knowledge is:
- 18 arcsec (3σ)

Observatory Level Pointing Knowledge Budget Comments

- The Observatory Level Pointing Knowledge Budget as presented provides real time absolute pointing knowledge that fully meets the Observatory Level Pointing Knowledge Requirement
- After the accuracies of on-orbit calibration and post-facto processing have been analyzed, a more relaxed On-orbit, Real-time Observatory Level Pointing Knowledge Requirement may be established
  - That may relax the requirements on some of the pointing contributors, primarily the Star Tracker / Periscope Assembly – to - Optical Axis Alignment Requirement
  - The selection of the Star Tracker is partly driven by TADS requirements (such as the knowledge of the distance between Fid-lights), therefore the benefits of any pointing requirements relaxation may be marginal

Observatory Level Pointing Control Budget

Telescope Pointing Control

Requirement	Predicted Performance
12 arcsec (3σ)	1.13 arcsec (3σ) On-axis 7.5 arcsec (3σ) XGS

RSS

Pointing Error (Star Tracker + TADS RSS'd)

Requirement (set in Knowledge Budget)	Predicted Performance (same as in Knowledge Budget)
.96 arcsec (3σ)	.88 arcsec (3σ)

Control System Performance

Sub-allocated Requirement	Predicted Performance
3 arcsec (3σ)	0.075 arcsec (3σ)

Calibration Error of Metering Structure X-Y Lateral Translations*

Sub-allocated Requirement	Predicted Performance (TADS Knowledge)
5 arcsec (3σ)	0.70 arcsec (3σ)

Metering Structure Torsion Translation (XGS only**)

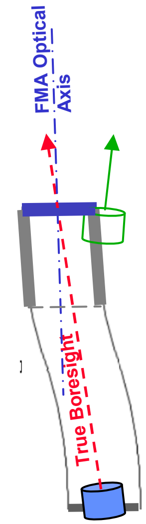
Sub-allocated Requirement	Predicted Wost Case Performance
10.4 arcsec (3σ)	0 arcsec (3σ) On-axis 7.4 arcsec (3σ) XGS

- *Image displacement due to M.S. Lateral Translations are compensated by "Observatory Off-pointing" (based on in orbit M.S Lateral Translations Calibration). Off-pointing nulls image displacements (within the error of the Calibration accounted for here) for all instruments except for the OP XGS in the Dispersion direction. To null that, a Translation Stage is required.*

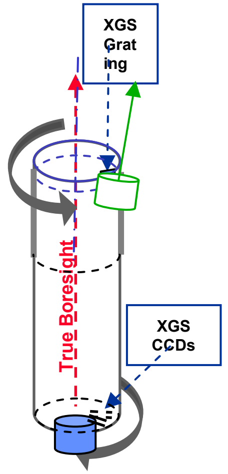
- *** This term is zero for On-Axis instruments*

Focus and Translation Mechanisms

- **Focus (+/-Z) Mechanism for XMS and WFI/HXI**
  - Max. Allowed On-axis Defocus in Z: +/- .15 mm
    - Expected total Metering Structure On-axis Defocus due to all effects in Z: +/- .06 mm
  - Note: On-axis Instruments don't need a Translation Mechanism, Metering Structure lateral translations induced pointing error is nulled by "Observatory Off-pointing".
- **Focus (+/-Z) Mechanism for the XGS (both CAT and OP)**
  - Max. Allowed On-axis + FIP Tilt Defocus in Z: +/- 0.3 mm (from XGS CAT PDD)
    - Expected total Metering Structure On-axis + FIP Tilt Defocus due to all effects in Z: +/- .075 mm
  - The Focus (+/-Z) Mechanism shall be able to also tilt the CCD Camera for best alignment with the Rowland circle.
    - A possible implementation is: two independent +/-Z mechanisms located near the extreme CCDs of the Camera Assembly
- **Cross-dispersion direction Translation Mechanism for the OP XGS (+/-X)**
  - Max. Allowed Cross-dispersion direction translation (in X for the OP) : +/- 1.6 mm
    - Expected worst case displacement of Image: +/- 3 mm
  - Translation Mechanism range of motion in one single axis: +/- 15 mm
  - Translation Mechanism accuracy: .05 mm
  - Note: No translation mechanism is needed for the dispersion direction (+/-X for the CAT XGS, +/-Y for the OP XGS).



Sine Mode



Torsion Mode

General Purpose IXO Actuator Requirements

- The Focus Mechanism shall used as its Actuator the "**General Purpose IXO Actuator**"
- The linear actuator selected for JWST fully meets IXO requirements and will be used for IXO

GENERAL PURPOSE IXO ACTUATOR PERFORMANCE REQUIREMENTS:

- Range of Motion in Z: +/- 25.0 mm
- Positioning Accuracy: 0.01 mm

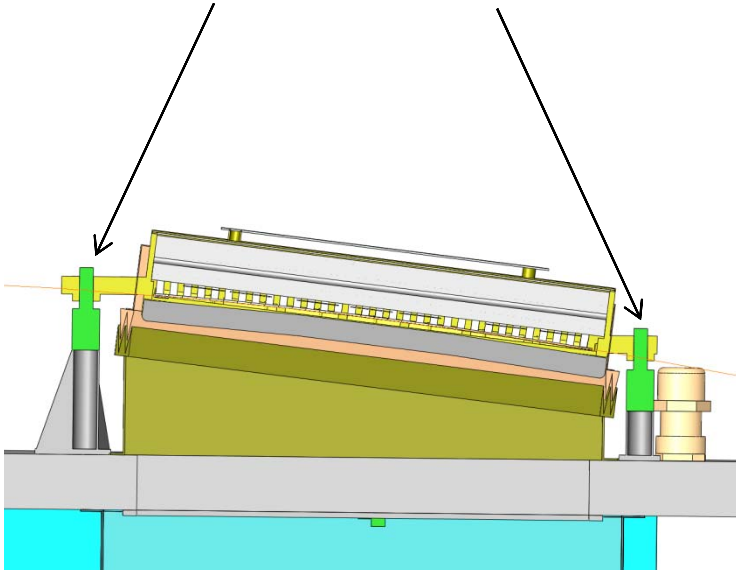
GENERAL PURPOSE IXO ACTUATOR FUNCTIONAL REQUIREMENTS:

- The General Purpose IXO Actuator shall survive 10000 operations over 10 years
- The General Purpose IXO Actuator shall be internally redundant and shall have internal metrology
- The General Purpose IXO Actuator shall bear the Launch Loads of the Instrument it supports, except for the XMS
  - The Launch Loads for the XMS are supported by the MIP Launch Lock Mechanism
- All General Purpose IXO Actuators shall be redundantly controlled from 6U Card(s) in the Instrument Module RIU

GENERAL PURPOSE IXO ACTUATORS USED ON IXO:

- 2 ea. For the Focus Mechanisms for the XGS
- 6 ea. For the Focus Mechanisms for the XMS and the WFI/HXI Instruments
- and if the OP XGS is used then also 2 ea. for the Cross-dispersion direction Translation Mechanism for the OP XGS (+/-X)

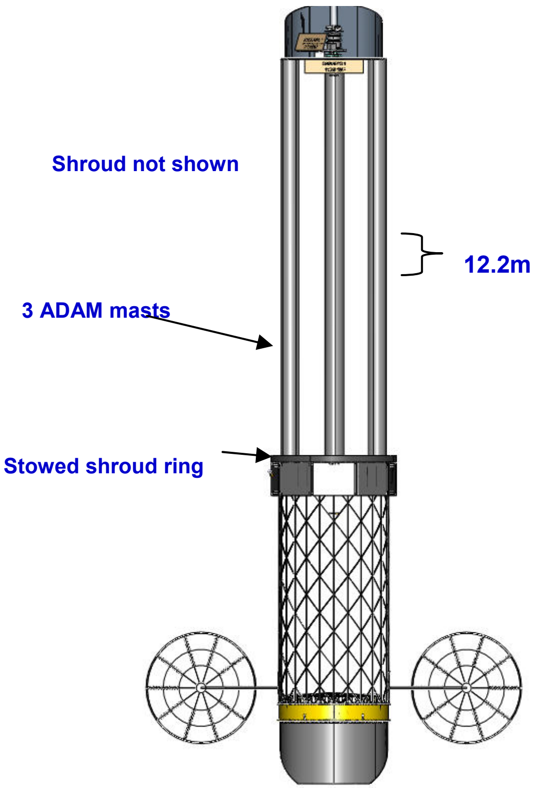
JWST Linear Actuator

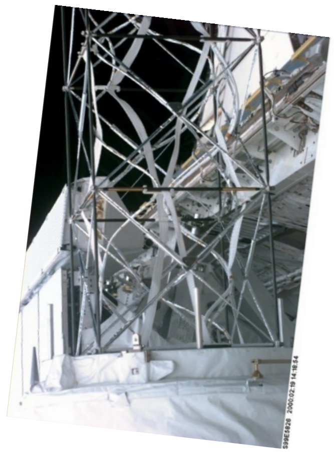


General purpose IXO actuator used as XGS Camera focus mechanism

Rigid and Flex Body Effects Calculations

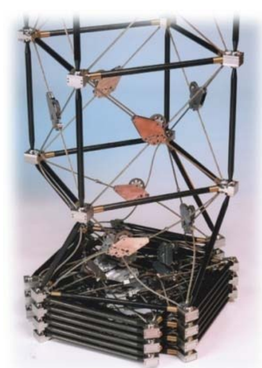
Deployment Module - Implementation of ADAM masts





3 ADAM masts
Stowed Size: 65cm diameter, 1m tall
Longeron CTE = 2*10^-7 / deg C

Longeron Diameter	1.37 cm
Longeron Cross Section Area	1.48 cm^2
Diagonal Cable Nominal Diameter	0.21 cm
Batten OD	1.14 cm
Batten ID	0.91 cm
Bay Length	.308 m
Mast Diameter through longeron centerlines	.592 m
Mast Length	12.2 m
Circle Radius for mast centerlines	1.64 m



Term		Parameters	Unit
Length	Deployed	12.2	m
Mass	Incl. complete 3 Mast System, Internal Harnesses, Deployment Controller, etc.	< 200	kg
Frequencies (from IXO FEM)	1st mode (bending) 2nd mode (torsion)	1.8 4.0	Hz Hz
Power	During deployment Deployed	< 600 0	W W
Push force during deployment / capable of deploying	▪ Instrument module ▪ "Pull-up" multi-layer Telescope Shroud sleeve (4.0 meter dia) w/ two baffles inside ▪ "Pull-up along-the-mast" harness	< 800 < 100 < 100	kg kg kg

Deployable Metering Structure Long Term Drift and Repeatability Vendor Data

Mast repeatability and long term drift deflections (thermal distortion is not included)

From: Messner, Dave [Dave.Messner@ATK.COM), Sunday, August 03, 2008

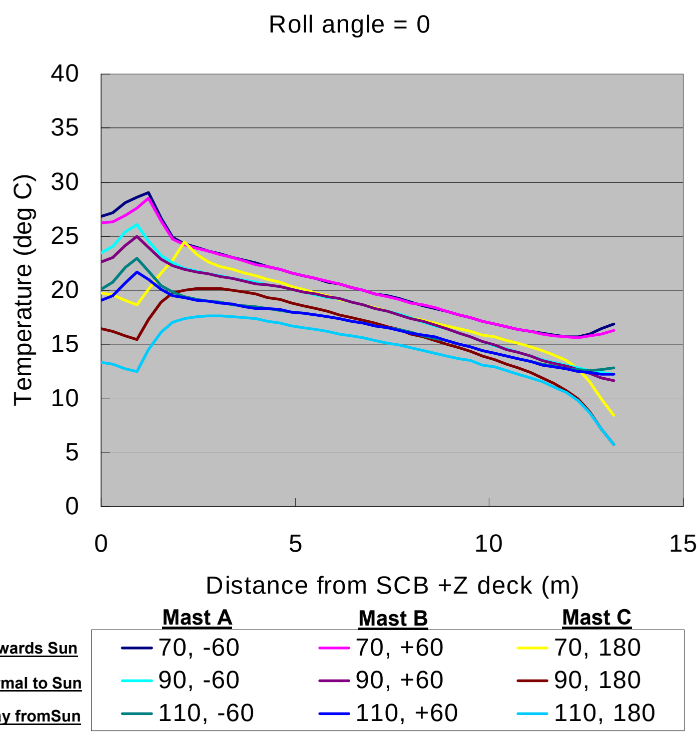
- **Long term drift** due to longeron ball seating, longeron coefficient of moisture expansion, diagonal ball seating, diagonal cable hysteresis, and diagonal cable creep**:**
  - **0.97 mm** **3σ lateral deflection for one mast, (mm)**
  - **0.018 mm** **3σ elongation for a mast, (mm)**
  - **0.558 mm** **3σ 3 lateral mast deflection, (mm)**
  - **0.026 deg** **3σ 3 mast twist, (deg) = 1.6 arcmin**
  - **6.6E-04 deg** **3σ 3 mast tip rotation, (deg)**
- **Repeatability** due to longeron ball seating, longeron coefficient of moisture expansion, diagonal ball seating, diagonal cable hysteresis, and diagonal cable creep**:**
  - **0.85 mm** **3σ lateral deflection for one mast, (mm)**
  - **0.012 mm** **3σ elongation for a mast, (mm)**
  - **0.49 mm** **3σ 3 mast lateral deflection, (mm)**
  - **0.023 deg** **3σ 3 mast twist, (deg)**
  - **4.5E-04 deg** **3σ 3 mast tip rotation, (deg)**

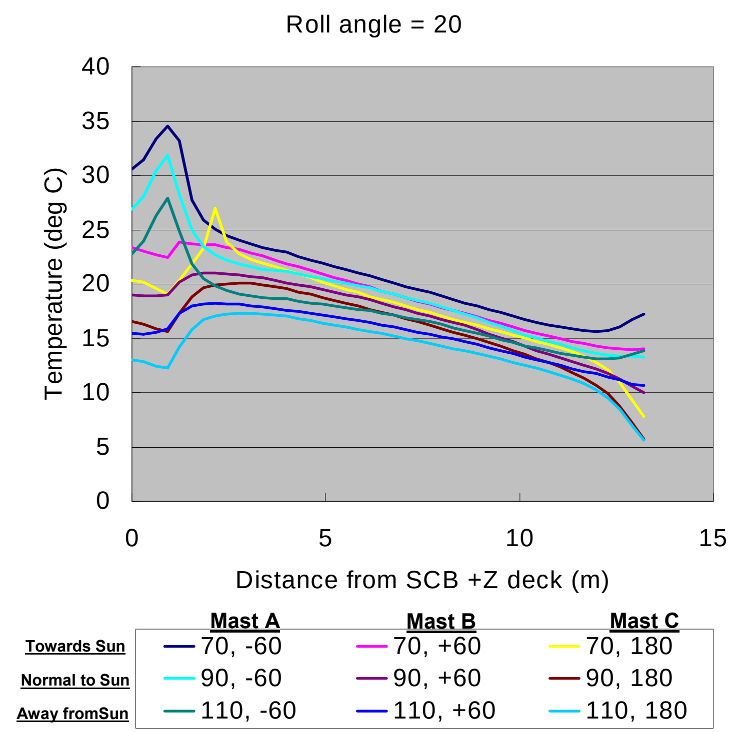
Note: Repeatability tests conducted on a six-bay engineering mast were within 2 sigma of calculated predictions for that mast.

Thermal Distortion Analysis - Mast Temperatures, Numerical Results

Basis of Calculations

- **The greatest composite average temperature difference between any two masts at any Sun angle is < 5 degC**
- **With a Longeron CTE = 2*10^-7 / deg C this temperature difference causes a Mast length difference of < 0.020 mm**





Legend: *First number is pitch angle, measured from telescope axis; Second number is mast angular position, measured from +X axis*

FIP Lateral Translations – All Instruments affected

Deflection calculations based on measured ATK data and CTE Calculations

Term	Definition	Expected Performance
Full Metering Structure Grand Total Deflections	Total Combined Static, Slow Changing, and Thermal effects	**+/- 1.0 mm in X and Y**
Full Metering Structure Deflections *(All Static and Slow Changing Effects combined)*	Static and Slow Changing position errors	**+/- 0.85 mm in X and Y** (estimate based on calc. below)
	Thermal Distortion	**+/- 0.15 mm in X and Y** (estimate based on calc. below)
Deployable Metering Structure only Deflections *(All Static and Slow Changing Effects combined)*	*Static and Slow Changing position errors*	*+/- 0.74 mm (RSS "A " & "B")* ▪ *"A ": 0.558 mm long term deflection for 3 masts* ▪ *"B": 0.49 mm repeatability deflection for 3 masts*
	Thermal Distortion	*+/- 0.1 mm (arc lengths assumed at full banana shape)*

• ***Note: one mm corresponds to ~10" (or 1 " to 100 um) at 20m***

XGS Grand Total Translations (FIP Lateral + Torsion)
Deflection calculations based on measured ATK data and CTE Calculations

Term	Definition	Expected Performance (Mast only)
XGS CAT Camera **Grand Total cross-dispersion axis displacement**	Due at all causes; Measured at r = 1500 cm	**< +/- 1.24 mm total lateral displacement** *(RSS)* •.FIP Lateral Translations: +/- 1.0 mm •.Torsion Translations: +/- 0.74 mm
FIP Torsion only displacement (causes tangential displacement of CCDs)	Measured at r = 1500 cm	**+/- .74 mm total tangential displacement** *(RSS)* • +/- 0.49 mm tangential displacement = 67.4 arcsec torsion, due to repeatability • +/- 0.558mm tangential displacement = 67.4 arcsec torsion, due to long term drift lateral deflection

- **Torsion has no first order effect on On-axis Instruments**

Metering Structure Lateral Translations Budget for On-Axis Instruments , XGS CAT, and XGS OP Dispersion Dir.

Lateral Translation calculations based on measured ATK data and CTE Calculations

Flown Down (as Item 3) from XMS Instrument Image Quality Error Budget

Metering Structure Lateral Translations **Boresight Misalignment relative to the FMA Optical Axis**	
Requirement	**Expected Performance**
XMS: +/- 3 mm (30 arcsec) XGS CAT: +/- 1.6 mm (16 arcsec)	+/- 1.25 mm (10 arcsec)

RSS

Lateral Translation due to Metering Structure Static and Slow Changing errors **(incl. Thermal induced deflections)**	
Sub-allocated Requirement	**Expected Performance**
+/- 2.99 mm	+/- 1.24 mm

Jitter **(outside of TADS bandwidth)**	
Sub-allocated Requirement	**Predicted Performance**
+/- 0.02 mm	+/- 0 .002 mm

- **Movement of the XGS OP images in the Cross-Dispersion direction due to the effects of Observatory Off-pointing may exceed the allowable range defined by CCD size, therefore the XGS OP requires a Cross-Dispersion Axis Translation Stage.**

Defocus

Defocus calculations based on measured ATK data and CTE Calculations

Requirement	Definition	Expected Performance	Stat
On-axis Instruments **(Axial defocus contribution only) :** **+/- 0.3 mm** **(per XGS CAT PDD)**	**Observatory Defocus on Z axis (Centerline)**	**Total Axial Defocus for the Full Metering Structure: < 0.06 mm (est'd)** *(This is the Expected Defocus performance for On-axis Instruments)* ----- *Axial - Depl. Metering Structure only contribution.: 0.04 mm (calc'd)* *(RSS "A " & "B", add "C" below)* ▪ *"A ": 0.018 mm 3σ repeatability elongation for a mast* ▪ *"B": 0.012 mm 3σ long term drift elongation for a mast* ▪ *"C": .018 3σ elongation for thermal (CTE .2 ppm/degC*	**(3σ)**
XGS **(Both Axial and FIP Tilt defocus contribution) :** **+/- 0.3 mm** **(per XGS CAT PDD)**	**Observatory Focal Length accuracy including relative local Focal Length delta measured between one end of the CAT CCD array at r = 700 mm and the other end at r = 1500 mm due to tilting of the FIP**	**Grand Total (Axial + FIP Tilt) Defocus for the Full Metering Structure: < 0.075 mm (est'd)** *(This is the Expected Defocus performance for the XGS)* ----- Total Axial Metering Structure contribution (as above): 0.06 mm FIP Tilt Contribution - Full Metering Structure: < 0.045 mm (est'd) *FIP Tilt Contribution - Depl. Metering Structure only.: 0.04 mm (calc'd)* (at 1.5 m radius, due to same effects as above)	**(3σ)**

- **Tilt of the FIP has no first order effect on On-axis Instruments**

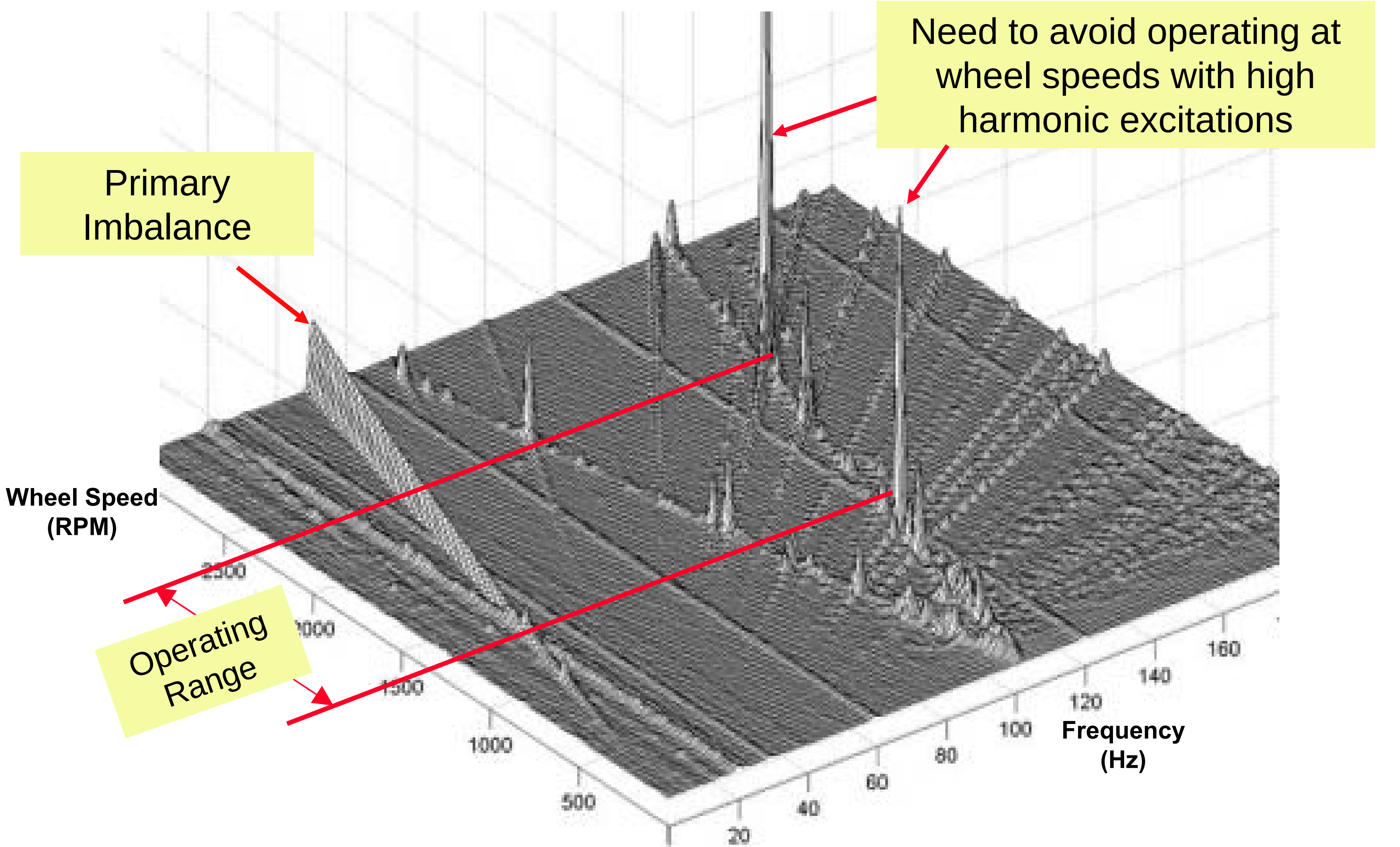
Note: one mm corresponds to ~10" at 20m

Control System Performance

ACS Performance

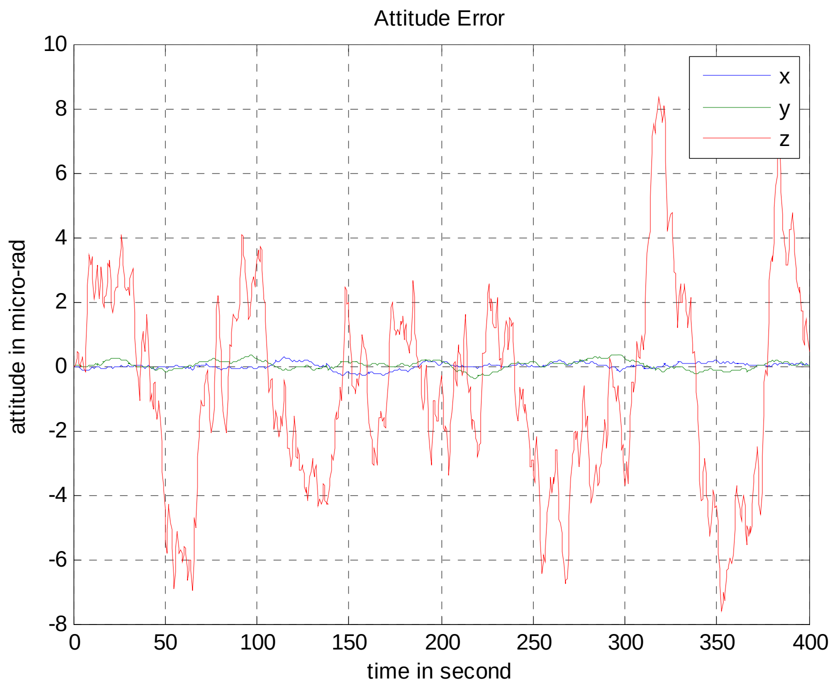
- Mass Properties
  - **Ixx = 320,000 kgm^2**
  - **Iyy = 320,000 kgm^2**
  - **Izz = 12,000 kgm^2**
- AST-301 Star Tracker Characteristics (used on Spitzer Space Tel)
  - **NEA = 0.15 arcsec (1 sigma before calibration) about X and Y axes, 4 arcsec about Z axis**
  - **2 Hz output**
  - **1 sec total latency (from center of integration to application of control torque)**
- RWL Torque Capability per Axis: 0.2 Nm (conservative)
- Digital Control (PID) with 0.02 Hz Bandwidth
  - **Uses Star Tracker Exclusively (gets better with Gyro, e.g. SIRU)**

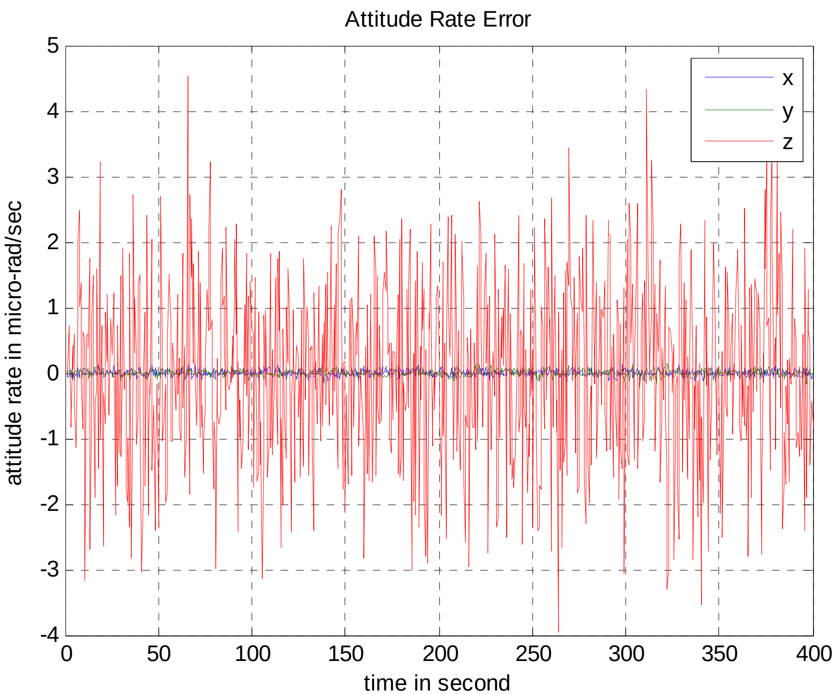
Reaction Wheel Disturbance Forces



Example Carpet Plot of In-plane Imbalance Forces From HR14 Dynamic Test

Pointing Performance





Spacecraft attitude errors due to LC

- **About X (1 sigma) = 0.025 arcsec***
- **About Y (1 sigma) = 0.025 arcsec**
- **About Z (1 sigma) = 0.64 arcsec**

**** Note: 1 arcsec = 4.85 micro-rad***

Spacecraft rate errors due to LC

- **About X (1 sigma) = 0.01 arcsec/s**
- **About Y (1 sigma) = 0.01 arcsec/s**
- **About Z (1 sigma) = 0.3 arcsec/s**

Analyses performed by Ich Pham (LMATC)

Slew Capability

- Calculated for four Honeywell HR16 wheels
  - In pyramid configuration (like Spitzer)
  - Pyramid apex in X direction
  - 30 deg cant angle (can be optimized depending on yaw ($\pm$180 deg) versus pitch ($\pm$10 deg) slew requirements)
- Each wheel
  - Angular momentum capability: 150 Nms
  - Torque capability: 0.2 Nm (is function of speed)
- Slew speed
  - 60 deg yaw: 0.52 hrs (margin not included)
  - 20 deg pitch: 0.41 hrs (margin not included)

Jitter

Jitter Analysis Parameters

- 150 N-m-s HR16 Wheel Imbalances (derived from datasheet)
  - Static = .72 g-cm, Dynamic = 23.1 g-cm^2
  - Only primary imbalance considered
  - Refined analysis will include affects of higher harmonics
- Use 0.5% modal damping
- Apply disturbances to all 5 wheels
  - RSS all wheels (conservative: assumes all wheels operate at same speed)
  - Calculate optical element jitter and LOS pointing error versus wheel speed
- Jitter is < 0.020 arcsec
  - Detailed analysis results are presented in Chapter 04 – Integrated Modeling

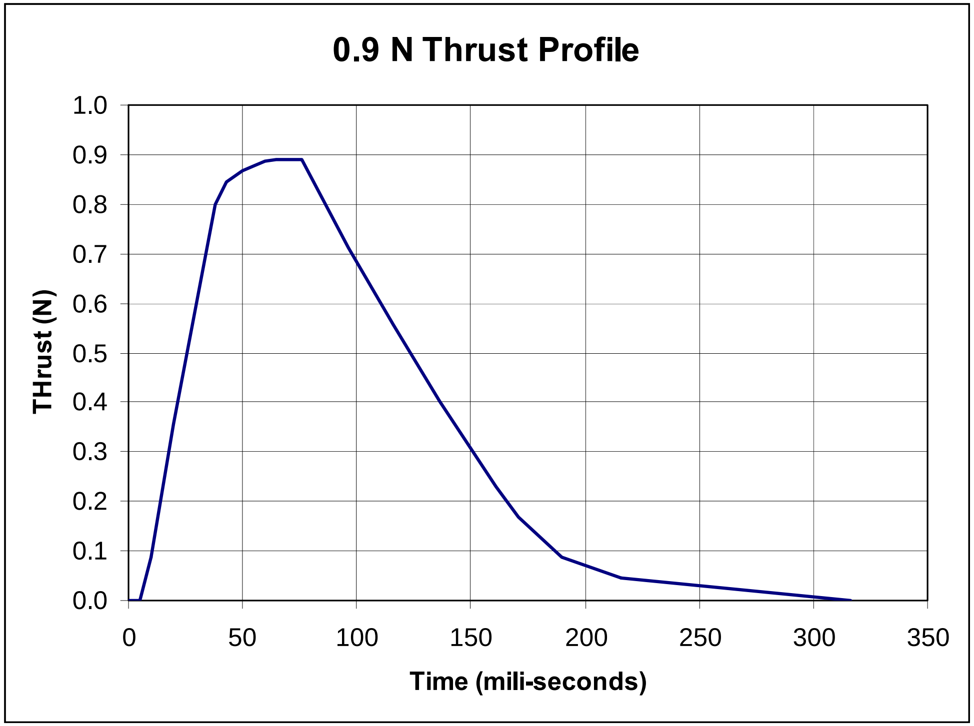
0.9 N Thruster Firing Effects

(The following slides duplicate much of the material presented in Integrated Modeling section)

Impact of Solar Pressure Offload (0.9 N Thruster) Firing

- Use highly reliable MR103H Aerojet thruster used for Voyager and Cassini
  - 2 sets of two .9 N thrusters spaced at +/-20 deg azimuth to place thrust vector on sunline even at roll angles other than zero
- Attitude Deviation versus Pulse Length
  - 0.11 s burn* every 18 minutes: 0.165 arcsec deviation
    - * When calculated as thrust from a single 0.9N Thruster on the sun line. For sum of two vectors from thrusters at +20 and -20 deg azimuths, adjust accordingly
- Number of Thruster firings:
  - 300,000 over 10 Years (once per 18 min)
    - Voyager had 500,000 burns from single thruster, using same thruster
  - Total amount of propellant: 25 kg
- Assumes IXO config with two 3.35 m dia Circular Ultraflex Solar Arrays

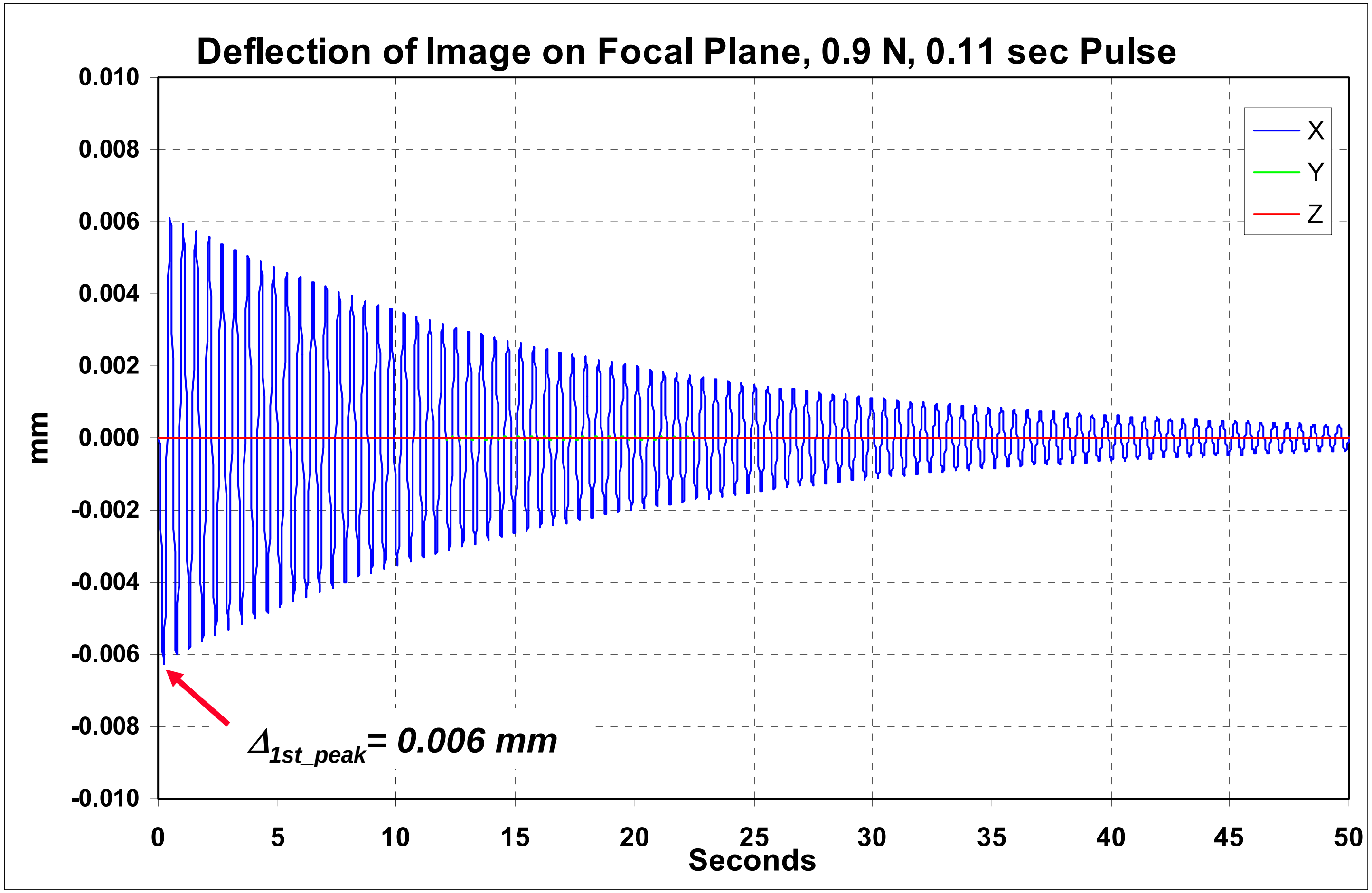
0.9N Thruster Pulse and Model Parameters



Total Impulse = 0.1 N-s
Derived from Astrolink jitter analysis profile

- **Modal damping = .5% of critical damping**
- **232 modes included in solution space (0 to 150 Hz range)**
- **2500 time steps at .001 second per step**

0.9N Thruster Firing Induced Vibration Decay

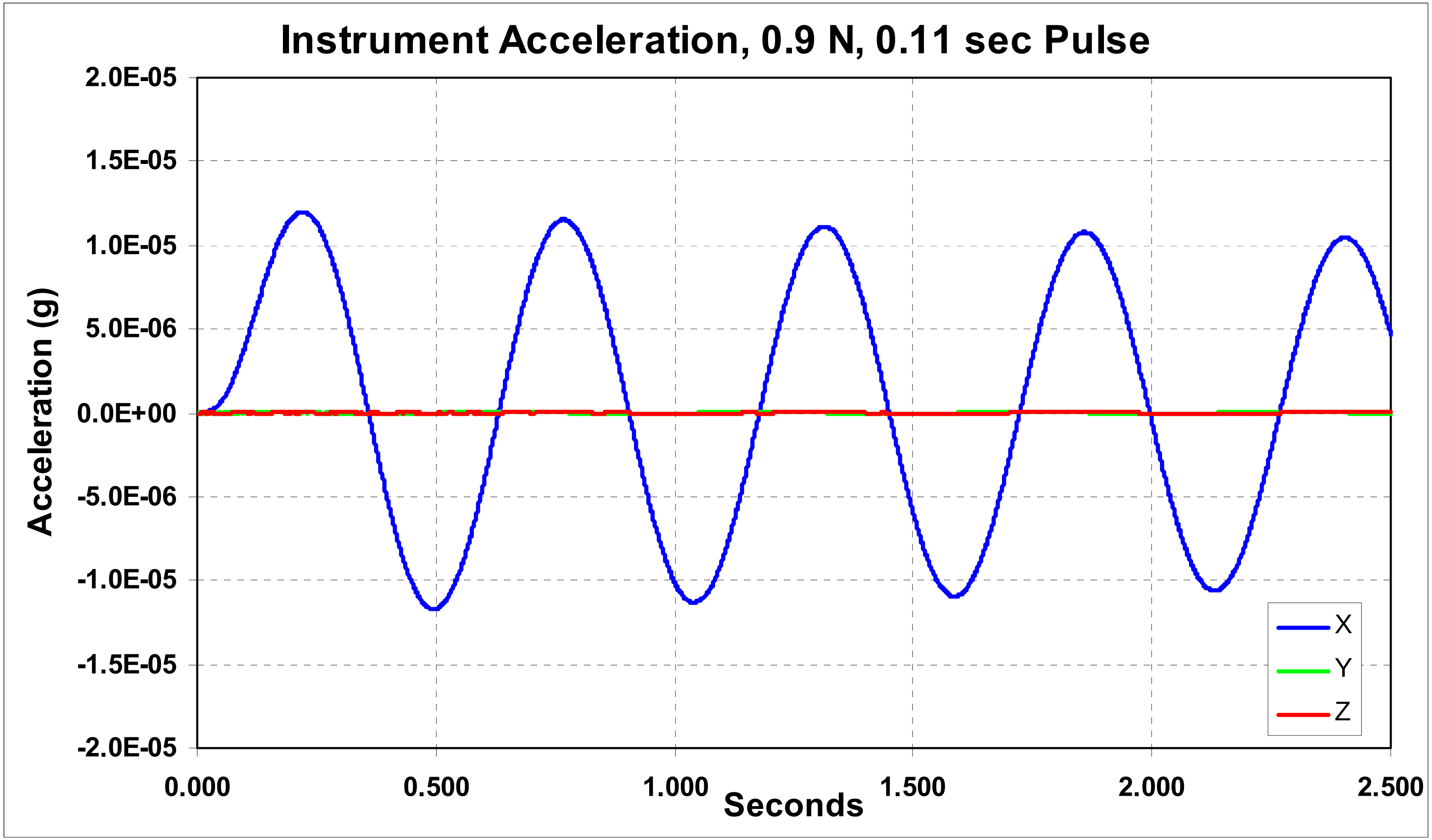


$$\frac{\Delta_{nth\_peak}}{\Delta_{1st\_peak}} = e^{-2\pi n\xi/(1-\xi^2)^{1/2}} \Rightarrow \Delta_{peak\_at\_time\_t} = 0.006e^{-.0575t}$$

Deflection Decays to less than .001 mm after 30 seconds

Integrated FEM + Control System Result

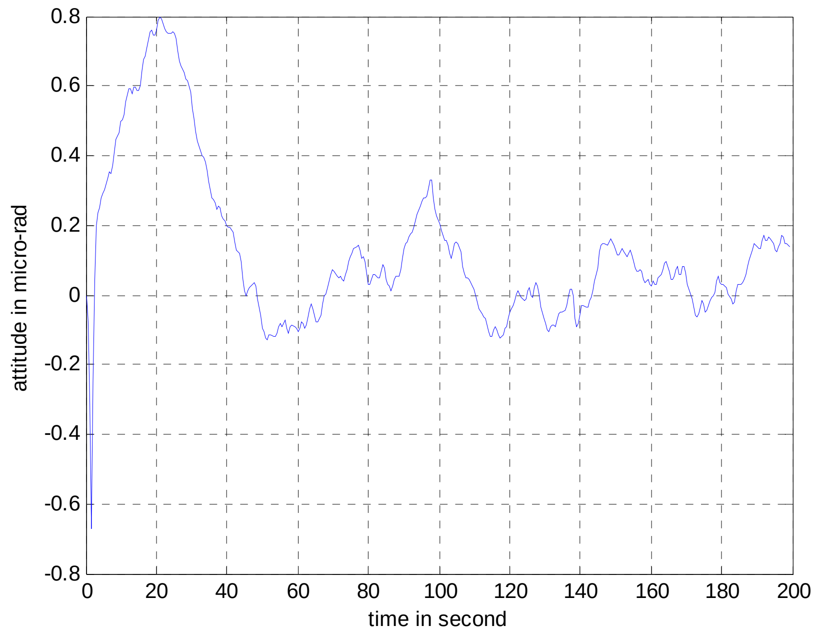
Accelerations due to 0.9 N Thruster Firing



Peak Acceleration = 12 micro-g

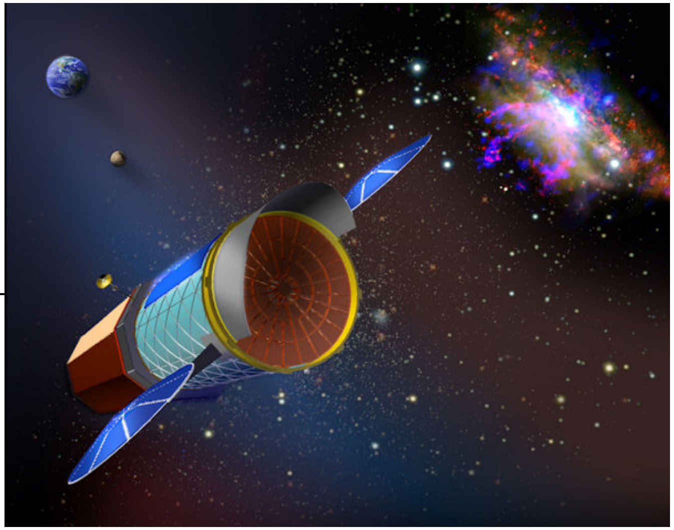
Integrated FEM + Control System Result
Temporary Attitude Deviation due to 0.9 N Thruster Firing

- 0.9 N Thruster on for 0.11 s; generates 0.1 Ns impulse and 0.62 Nms angular momentum delta
- RWL feed forward of -0.2 Nm for 3.1 seconds
- Thruster firing centered relative to 3.1 second RWL feed forward period



- Resulting attitude excursion about Y axis during burns: 0.165 arcsec; meets IXO pointing requirements

IXO Systems Definition Document
Chapter 7



Spacecraft Subsystems Overview

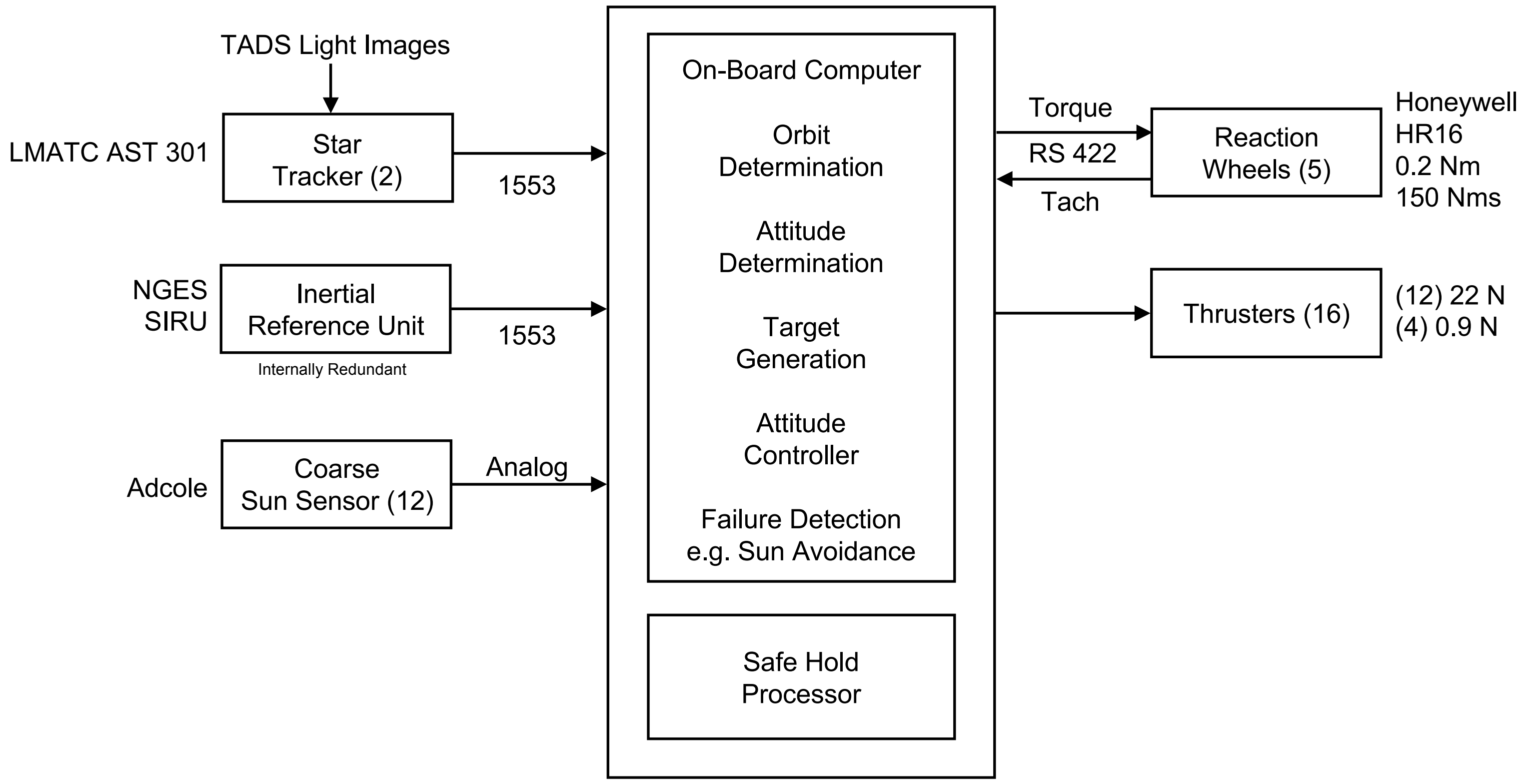
GN&C Hardware

(For performance, see the POINTING Chapter)

ACS Overview

- Three-axis stabilized, inertial pointing
  - X axis points to Sun, Z axis points to science target
  - Solar panels pointing towards sun maintained for all modes: Science, slew, maneuver, safe hold, and cruise
- Two AST 301 Star Trackers
  - Coaligned with telescope boresight to provide precision forward pointing attitude knowledge
  - Also used as part of the Telescope Aspect Detection System (TADS) to provide precision rear pointing attitude knowledge
- IRU mounted on S/C Bus
  - Internally redundant
- Five reaction wheels arranged in a JWST-like “L-infinite configuration to maximize momentum, biased for a 4:1 or greater ratio between the X/Y axis and the Z axis
  - RWL Torque Capability per Axis: 0.2 Nm (conservative)
  - Slews require authority mainly in the X axis
  - Momentum accumulation primarily in the Y axis
- Nearly continuous low disturbance thruster based solar torque unloading allows uninterrupted science observations
- Digital Control (PID) with 0.02 Hz Bandwidth
- The control system accommodates the small (5.6 cm) migrations of the observatory center of mass caused by movements of the MIP
- Mass Properties
  - Ixx = 320,000 kgm^2, Iyy = 320,000 kgm^2, Izz =   12,000 kgm^2

ACS Block Diagram



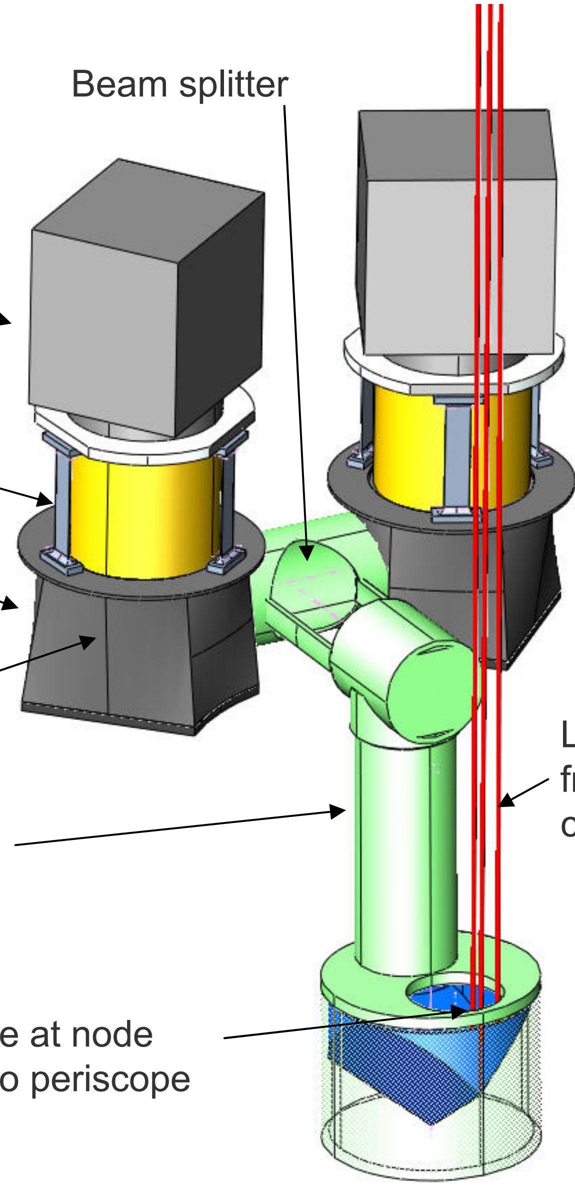
ACS Modes of Operation

	Sensors			Actuators	
MODE	Star Tracker	Gyro	CSS	Wheels	Thrusters
Science	X	X		X	X (0.9 N pulses)
Slew	X	X		X	
Thrust	X	X			X
Cruise	X	X		X	X
Safe Hold		X	X	X	X

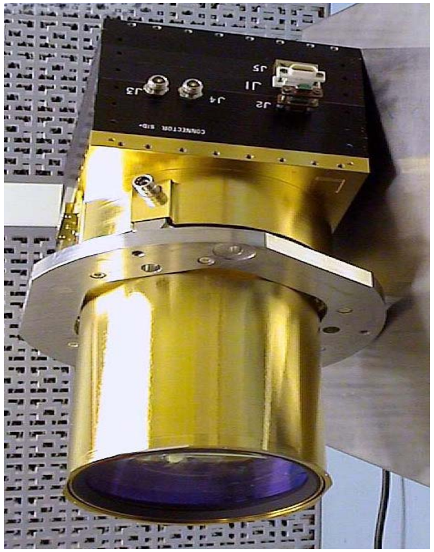
Star Tracker and TADS Specifications and Performance

Star Tracker and TADS specifications and performance are described in Chapter 06 - Pointing

TADS Components



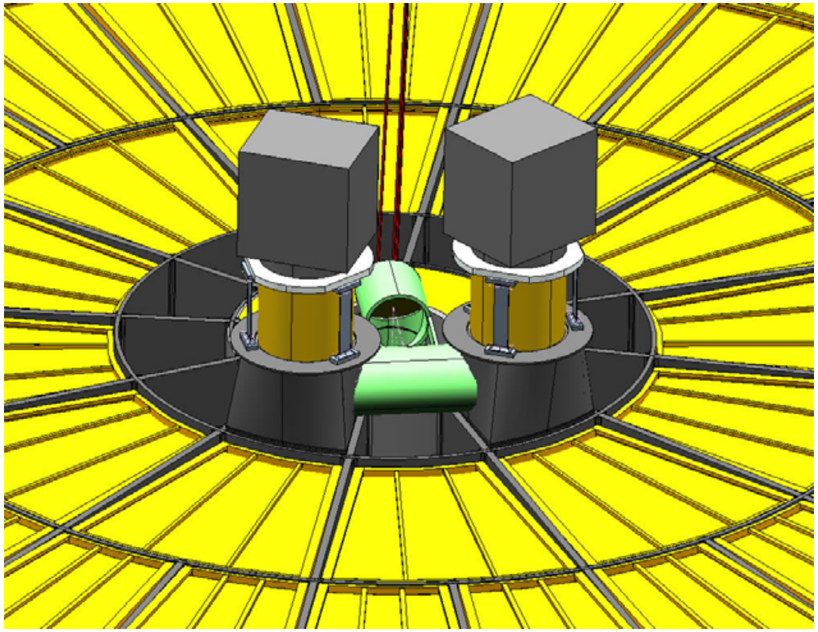
AST-301 Tracker

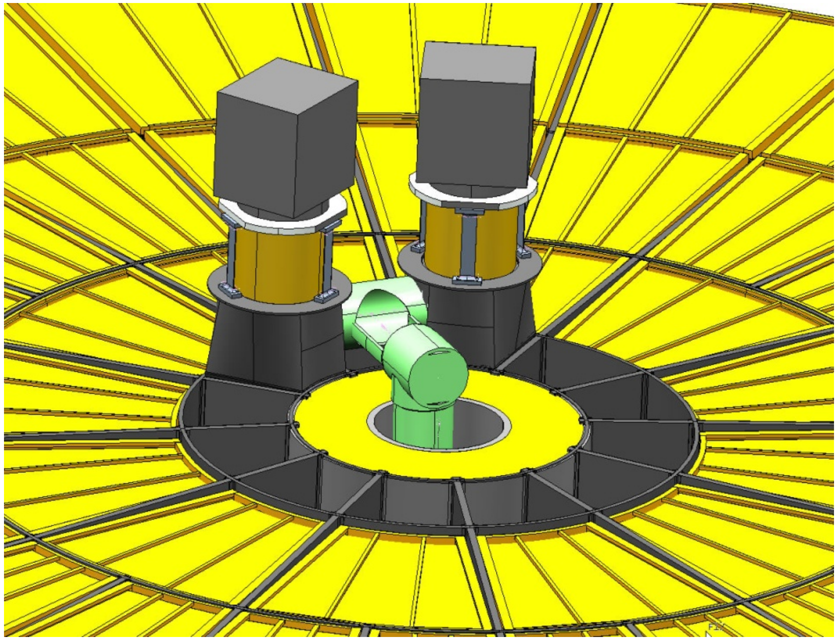


FID Light (LED light) assembly, 45 mm long

TADS Mounting provides Optical Bench quality alignment of Star Tracker / Periscope Assy to the FMA Structure

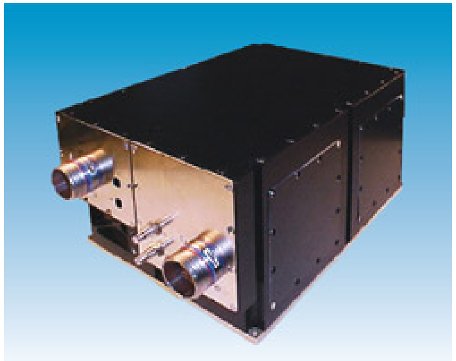
- Provides Star Tracker to Periscope coalignment with minimal on-orbit variation
  - A stand elevates the tracker lens assembly about 12 cm above the FMA, to clear area for Periscope
  - Tracker mounts to 3 blade flexures via its Invar mounting flange, flexures mount to top of the stand
  - The periscope tube enters the stand where a fold mirror is located to turn the beam up and into the tracker FOV





Adcole Coarse Sun Sensor and SIRU

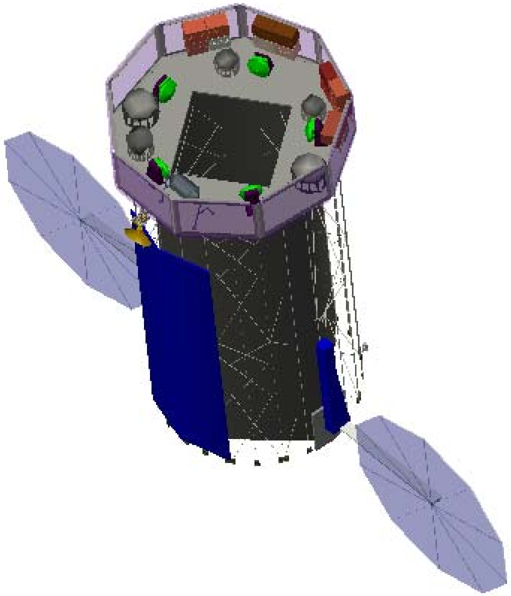
- Individual CSS detectors provide 2π steradian coverage
- 12 detectors distributed across the observatory provide redundant full 4π steradian coverage



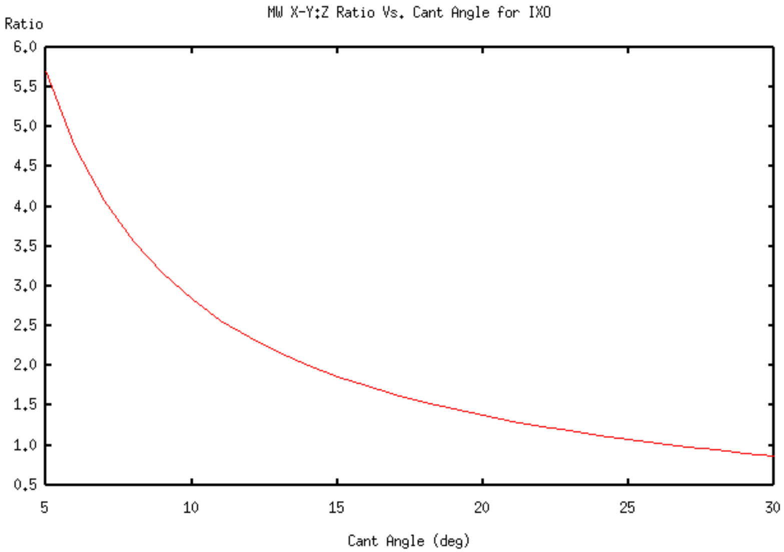
- Manufacture NGES
- Technology HRG 3 axis
- Gyro Performance
  - Angle Random Walk 0.00015 deg/rt-hr
  - Angle White Noise 0.003 arcsec/rt-Hz
- Range 12 deg/sec
- Units Required 1 (internally redundant)
- Data Interface RS-422/1553
- Mass 4.5 kg
- Power 38 W
- Size 18 x 15 x 29 cm
- Cost $1500 k

Reaction Wheel: Honeywell HR 16-150

- Momentum Storage
  - 150 NMS
- Reaction Torque
  - 0.2 Nm
- RS 422 I/F
- Mass: 15 kg per unit
  - HR(16) series rated at TRL-7

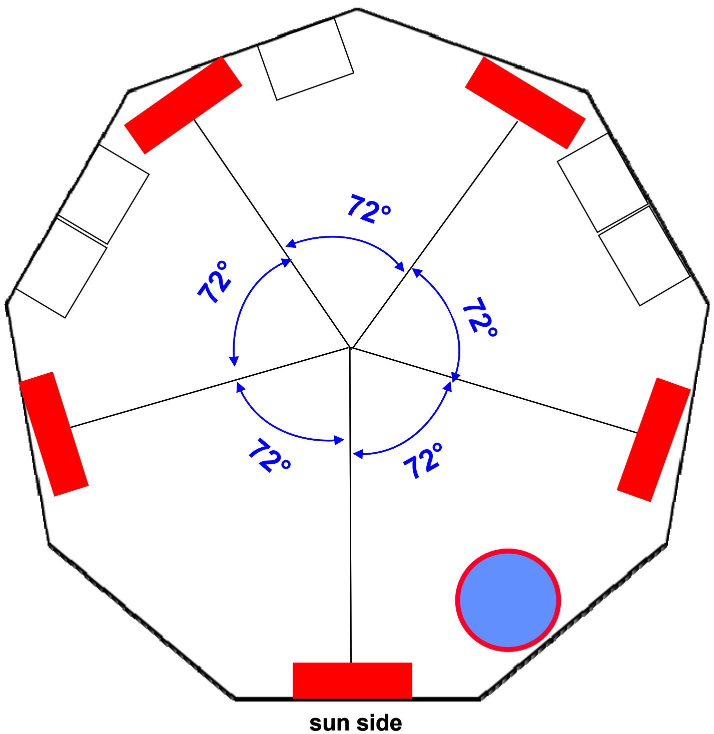


Proposed Reaction Wheel Orientation



Cant angle selected based on desired X-Y:Z ratio
A 4:1 ratio results in ~ 7 deg cant angle

Reaction wheels canted slightly up out of page



Reaction Wheel Configuration Slew Capability

- Calculated for five Honeywell HR16 wheels
  - In pyramid configuration (like Spitzer)
  - Pyramid apex in Z direction
  - < 10 deg cant angle (can be optimized depending on yaw ($\pm$ 180 deg) versus roll ($\pm$ 10) slew requirements)
- Each wheel
  - Angular momentum capability: 150 Nms
  - Torque capability: 0.2 Nm (is function of speed)
- Slew speed
  - 60 deg yaw: 0.52 hrs (margin not included)
  - 20 deg pitch: 0.41 hrs (margin not included)

Solar Pressure Offload with 0.9 N Thruster Firing

- **Attitude Deviation versus Pulse Length**
  - **Max. 0.11 sec burn* every 18 minutes: 0.165 arcsec deviation**
    - *** 0.11 sec calculated for thrust from a single 0.9N Thruster located anti-sun. For the sum of two vectors from thrusters at +20 and -20 deg azimuths, adjust accordingly**
- **Number of Thruster Firings:**
  - **300,000 over 10 Years (once per 18 min)**
    - **Voyager had 500,000 burns from single thruster, using same thruster**
- *Solar Pressure modeling assumes two 3.4m dia Circular Ultraflex Solar Arrays*

Thermal

Orbit Thermal Environment

- L2 provides excellent steady thermal environment. Thermal disturbances only from
  - Sun angle changes due to varying roll and pitch angle (effects can be calibrated)
  - Seasonal and random variations of solar radiation
- Ideal for passive (radiative) cooling
  - Zero % eclipses during entire mission
  - Earthshine and Moonshine negligible
- Charged particles environment requires electrically conductive thermal coatings

Observatory Thermal Design Approach

- The Thermal subsystem is conventional, and uses only standard off the shelf satellite thermal control technology, such as radiators, heaters, and Variable Conductance Heat Pipes
- “On” and “Off” instrument electronics share common radiators to increase efficiency
- All components in the Thermal subsystem are at TRL 8 or 9, most are available COTS

Payload Temperature Requirements

Payload	Element	Operating	Annealing	Survival - (Off)
XMS	Dewar Assembly	-33C to 27C		-100C to 50C
	Filter Wheel Mechanism	-20C to 50C		-20C to 50C
	Pre-Amplifier/BiasBox (PBB)	-20C to 50C		-30C to 70C
	Feedback/Controller Box (FCB) -1	-20C to 50C		-30C to 70C
	Feedback/Controller Box (FCB) -2	-20C to 50C		-30C to 70C
	Feedback/Controller Box (FCB) -3	-20C to 50C		-30C to 70C
	Feedback/Controller Box (FCB) -4	-20C to 50C		-30C to 70C
	Pulse Processing Electronics (PPE)	-20C to 50C		-30C to 70C
	ADR Controller Electronics Box(ADRC)	7C to 27C		-30C to 70C
	Pre Cooler Compressor	10C to 40C		-20C to 50C
	Cryocooler Control Electronics (CCE)	10C to 40C		-30C to 70C
	Filter Wheel Control Electronics (FWC)	10C to 40C		-30C to 70C
	Power Distribution Unit (PDU) -1	10C to 40C		-30C to 70C
	Power Distribution Unit (PDU) -2	10C to 40C		-30C to 70C

Instrument Thermal Interface Requirements				
Payload	Element	Operating	Annealing	Survival - (Off)
(WF&HX)I	Focal Plane Array [(WF&HX)I-FPA]			
	Focal Plane Array - cold part	-63 +/- 0.1 C		-103 to 77 C
	Focal Plane Array - warm part	0 to 40 C		-40 to +85 C
	HXI Sensor Head (HXI-S)	-20 +/- 2 C	5 ±2 C	-40 to +40 C
	WFI Hemisphere Pre-Processor-1	0 to 40 C		-40 to +85 C
	WFI Hemisphere Pre-Processor-2	0 to 40 C		-40 to +85 C
	HXI Analog Electronic Unit (HXI E)	0C to 40 C	0C to 40 C	-40 to +40 C
	WFI Frame Builder / Brain Box - (FBB) 1&2	0 to 40 C		-40 to +85 C
	WFI Power Conditioner Unit -1 (control)	0 to 40 C		-40 to +85 C
	WFI Power Conditioner Unit -2 (control)	0 to 40 C		-40 to +85 C
	HXI Digital Electronics (HXI D)	0C to 40 C	0C to 40 C	-40 to +40 C

Payload Temperature Requirements, cont'd

	Instrument Thermal Interface Requirements			
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**
XGS	Grating Array Assemblies	20 +/- 1 C		18 to 53C
	CCD Camera Structure	-30 to 10C		-120 to 70C
	Paddle and CCD Assembly	-90 +/- 10C		-120 to 70C
	Detector Electronics Assembly Box (DEA)	-30 to 10C		-30 to 55C
	Digital Processing Assembly Box (DPA)	-30 to 10C		-30 to 55C

	Instrument Thermal Interface Requirements			
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**
XPOL	Focal Plane Assembly (XPOL-FPA)			
	GAS Pixel Detector (GPD)	+5 ±1 C		-15 to +45 C
	Filter Wheel (FW)	0C to 40C		-15 to +60 C
	Backend Electronics (BEE)	0C to 40C		-15 to +60 C
	Control Electronics (CE)	0C to 40C		-15 to +60 C

	Instrument Thermal Interface Requirements			
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**
HTRS	Focal Plane Assembly (HTRS-DEU)			
	SDD Array	-20 +/- 2 C		-40 to +35 C
	Detector Electronics Unit + Filter Wheel	0C to 40C		-40 to +35 C
	Central Electronic Unit (HTRS-CEU)	0C to 40C		-40 to +35 C

Spacecraft Bus Components Operational Temperature Requirements

- Electronics Components
  - Typically -10° C to +40° C (-20° C to +50° C survival)
- Release Mechanisms and Actuators
  - -20° C to +50° C
- Solar Array Temperatures
  - -100° C to +100° C
- Li Ion Battery Temperatures
  - 0° C to +30° C
- Propulsion Components
  - Fuel lines +10 to +40 C
  - Thruster valves +10 to +40 C
  - Hz Tank +10 to +40 C
  - PCM +10 to +40 C
  - F&D +10 to +40 C
  - NTO Tank - 10 to +40 C
- HGA
  - Gimbal Motors 0° C to 50° C
  - Damper -15° C to 35° C

FMA Thermal Requirement

- Mirror segment spatial temperature requirement in operating mode
  - 20° C±1° C
    - 24 outer modules with 206 segments per module
    - 24 middle modules with 230 segments per module
    - 12 inner modules with 286 segments per module
  - ±0.5° C within SXT module
- Mirror segment temporal temperature requirement
  - ±0.1° C temperature stability in operating mode
    - Heater controller tolerance specification
- Survival temperature limits
  - 10° C minimum and 30° C maximum
- Electrically conductive thermal coatings required

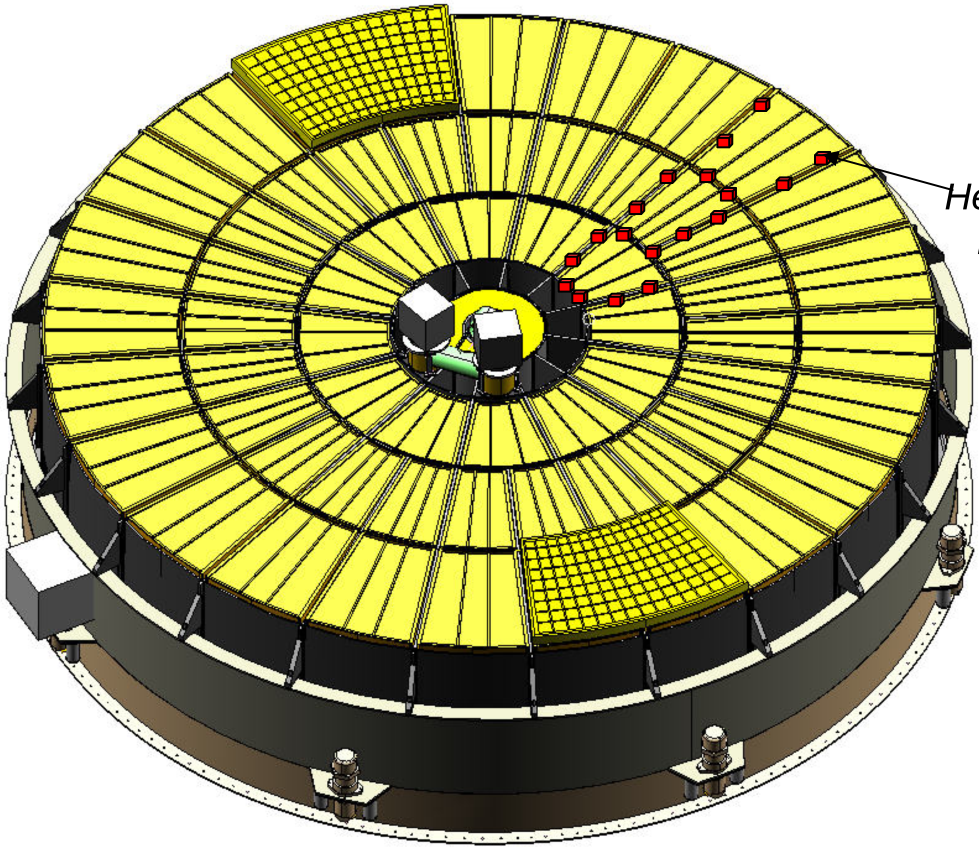
FMA Thermal Design

- Active heater control
  - Multiple heater zones on stray light baffles, module enclosure and section of metering structure adjacent to FMA
- MLI on exterior of metering structure and, as much as possible, adapter
- Cold-biasing FMA to allow active heater control and minimize heater power
  - Conductive silver composite coating (low absorptance and high emittance) on adapter MLI outer cover
    - GGS WIND and POLAR, and IMAGE LENA flight heritage
  - 50% conductive silver composite coating and 50% Germanium Kapton (alternate stripes) on metering structure MLI outer cover
    - Germanium Kapton has *Swift* BAT flight heritage
  - Conductive silver composite coating on sunshade sun side
- Collimator/stray light baffle reduces view of mirror segments to space

Approach to SXT Heater Controller Layout Minimizes Harness Mass

Distributed Heater Controller Approach:
Use multi-channel and small heater controllers, like those flown on Swift BAT.*
Mount module heater controllers to structure members adjacent to each module.
Mount metering structure heater controllers to metering structure adjacent to heater.

Adjustable set point in flight.
Heater controller set points changed to 12°C in non-operating or safehold Mode. This approach eliminates need for survival heater circuits.



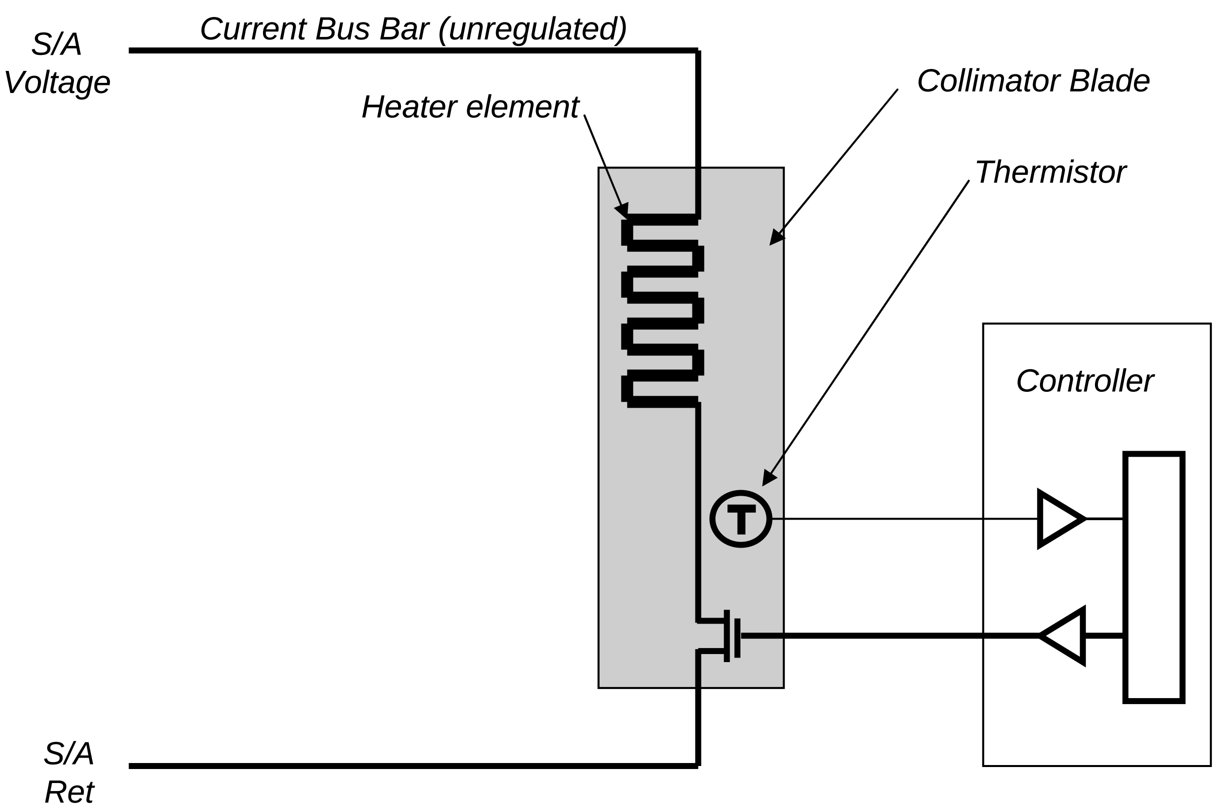
7.57 cm x 10.48 cm x 2.70 cm and 0.22 kg each. Adjustable set point in flight.

FMA Thermal Control – Independent Power System

- Observatory to maintain Survival Mode indefinitely (even after LV Separation w/ no S/As deployed)
- The body mounted solar array, combined with a Sun-positive Safe-Mode allows maintaining FMA Temperatures
- FMA Temperature Controller has independent unregulated power system: S/A output directly to Heaters
  - About half of the strings on the body mounted array are dedicated to the FMA and are routed directly to the FMA Temperature Controller
- FMA Temperature Controller regulates directly to Temperature regardless of voltage or current
  - Single FET
  - Every W dissipated in the FETs is used: FETs are also mounted on the Pre-Collimator Blades

FMA Temp Control Regulates directly on Temperature

- FMA Heater power is not voltage regulated (to increase efficiency)
- Control system regulates current directly on Temperature

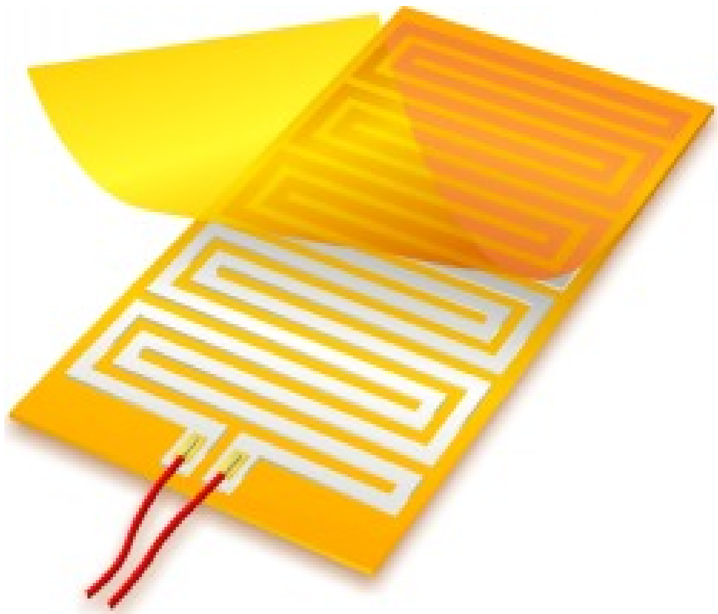


FMA Thermal Control - Kapton Foil Heaters

- Shaped to the precise size of the collimator blades for uniform (or shaped) heat distribution
- Custom shaping, integrated connector terminations and integrated thermistors simplify harnessing
- Kapton Foil Heaters flew numerous NASA missions

Thermofoil™ Heaters

Thermofoil™ Solutions for Heating



Thermofoil™ heaters are thin, flexible heating elements consisting of an etched foil resistive element laminated between layers of flexible insulation. Since their introduction by Minco over 45 years ago, Thermofoil™ heaters have demonstrated significant advantages over conventional electric heaters:

Propulsion

Propulsion Subsystem Drivers

- Be able to load propellant for the ELV Throw mass limited max IXO wet mass of 6135 kg (i.e. 229 kg propellant)
- Provide Thruster Suite For Six Degrees Of Freedom
- Provide Max Thruster Arm For Reaction Wheel Offload
- Size Prop System for Ten Year Mission Life
- Design with Flight Heritage Components
  - Minimizes qualification cost and flight/schedule risks
  - No customization for mass saving
- Design For Single Fault Tolerance
  - No credible single point failures (GSFC-STD-1000, Rule 1.05)
  - Dual fault tolerant where required by range safety
- Minimize Contamination to Optically Sensitive Surfaces
  - Locate thrusters to minimize S/C plume impinge and provide no direct line of sight between thruster nozzles and optically surfaces

Mission Delta-V, Propellant, and Margins Analysis

DELTA V BUDGET FOR 10 YEARS				
	Estimate	ACS Tax	Contingency	Subtotal
Launch Window	10 m/sec	5%	0%	11 m/sec
ELV Dispersion Correction	20 m/sec	5%	0%	21 m/sec
Mid-Course Correction	10 m/sec	5%	5%	11 m/sec
Orbit Lowering Maneuver	0 m/sec	5%	0%	0 m/sec
L2 Stationkeeping for 10 years	40 m/sec	5%	5%	44 m/sec
Momentum Management for 10 years	9.8 m/sec	0%	5%	10 m/sec
De-orbit	1 m/sec	5%	5%	1 m/sec
Total Equivalent Delta V [m/s]				98.0

ALLOCATION PROPELLANT BUDGET	
	Allocation
Allocation Dry Mass	4929.9 kg
Prop Mass (use equivalent Isp =275)	182.1 kg
5% Ullage and Residual	9.1 kg
Allocated Propellant Mass	191.2 kg

- Biprop Thrusters Isp > 278 s
- Monoprop ACS thruster Isp > 150 s
- Composite Mission Isp = 275.5 s
- Momentum management delta-v apportioned to ACS thrusters (for 10 years): 5 m/s CBE, 7 m/s MEV => 25 kg MMH

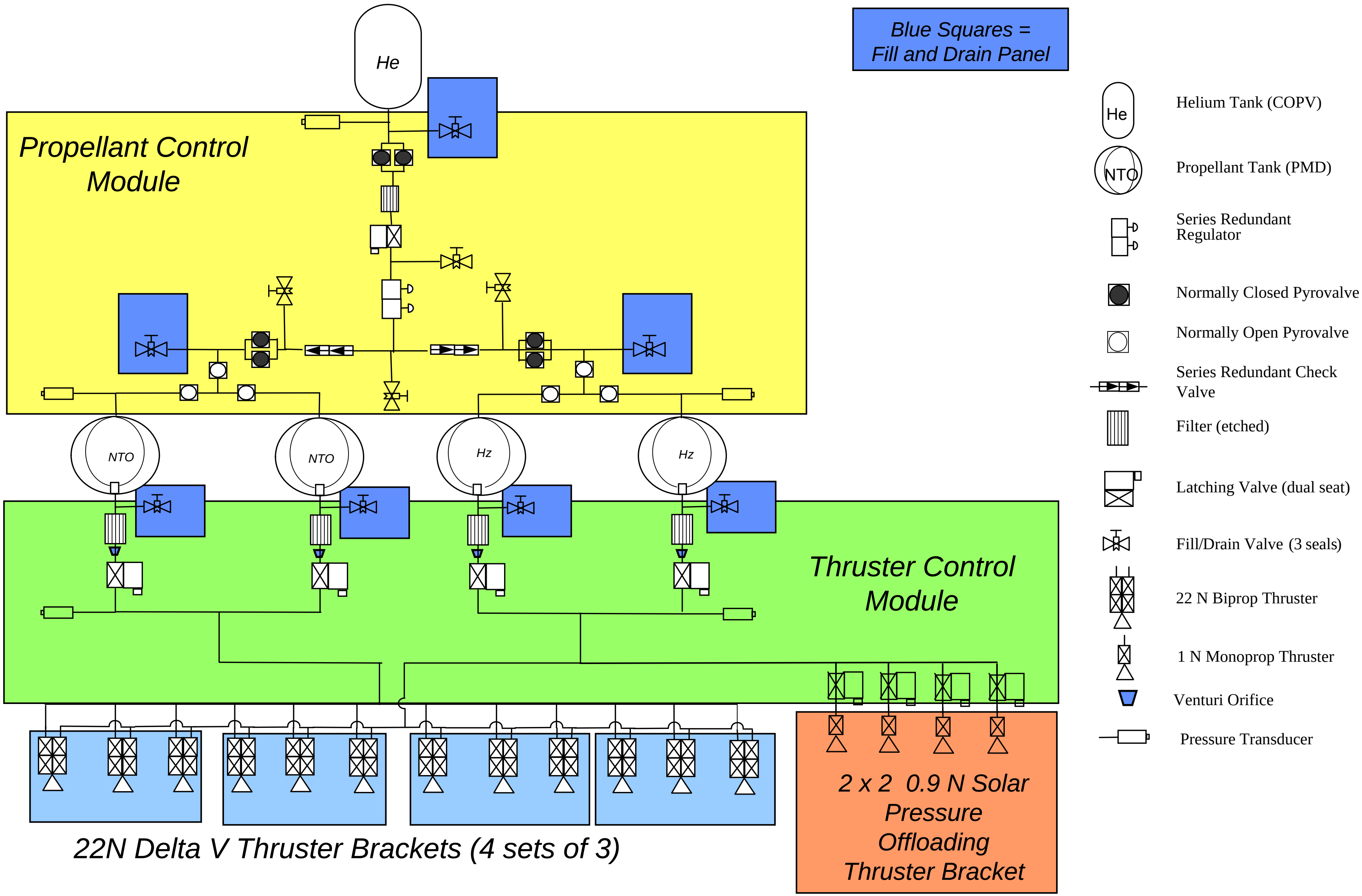
Margin Analysis w/ Allocated Wet Launch Mass of:	5121 kg	
Tanks max load Propellant mass	281.0 kg	
Tanks max load Propellant mass margin	47.0%	rel. to Propellant required for nominal Delta-v
Tanks max load Delta-v [m/s]	142.7	
Tanks max load Delta-v margin	45.6%	rel. to nominal Delta-v

Margin Analysis w/ max LV Throw Mass of:	6425 kg	
Tanks max load Propellant mass	281.0 kg	
Tanks max load Propellant mass margin	12.8%	rel. to Propellant required for nominal Delta-v
Tanks max load Delta-v [m/s]	115.1	
Tanks max load Delta-v margin	17.4%	rel. to nominal Delta-v

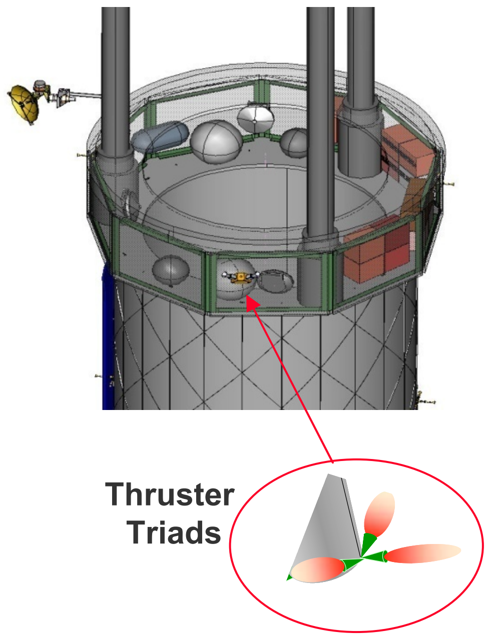
Propulsion Subsystem Description

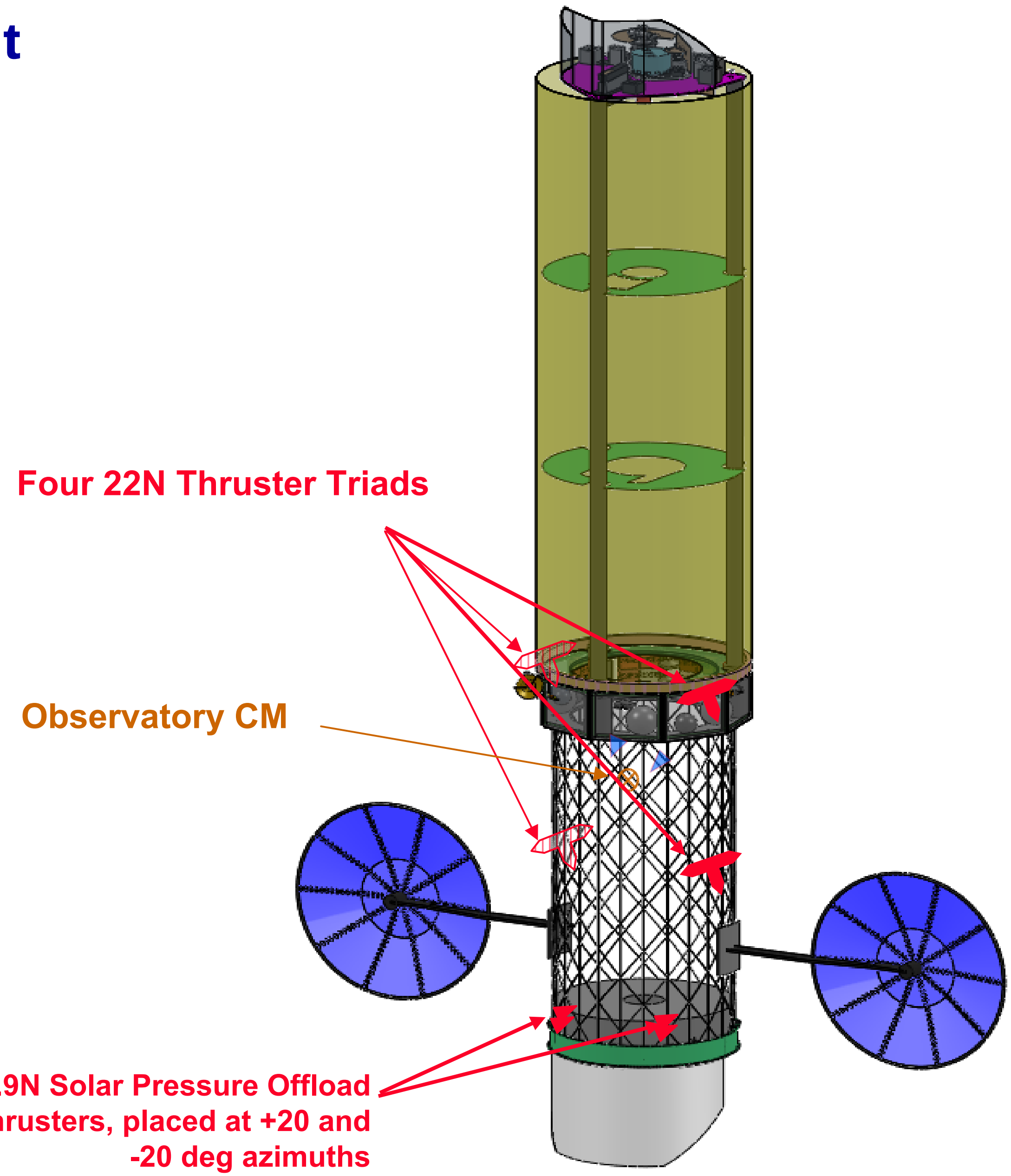
- Pressure Regulated, NTO/Hz, Bipropellant Propulsion Subsystem
  - Tanks allow for a maximum of 151 kg NTO and 130 kg Hz = 281 kg of Propellant Load (at Mass Mixture Ratio = 0.86)
  - To mitigate Pressure Regulator lifetime concerns, a trade is to be performed on switching after L2 orbit injection from pressure regulated mode to blowdown mode (similar technique is used on commercial GEO communication satellites)
- Twelve Single String, 22 N Biprop ACS And Station Keeping Thrusters
- Four (two + two redundant) MR-103 0.9 N ACS Thrusters for Solar Pressure Offloading
- Monolithic Titanium NTO & Hz Tanks (2 each)
- One COPV Titanium He Tank
- Series Redundant He Regulator With High Pressure Isolation Latch Valve For Long Life Operation
- Propellant Manifolds & Components Are All Titanium
- Venturi Orifices Below Fuel Filters To Minimize Water Hammer Surge Pressure During Thruster Priming
  - Required by Goddard GOLD Rules
  - Fuel flight manifold test simulators required to flow test Venturi orifice surge & flow loss performance

Propulsion Subsystem Block Diagram w/ Modules



Thruster Placement





Key Ops Parameters

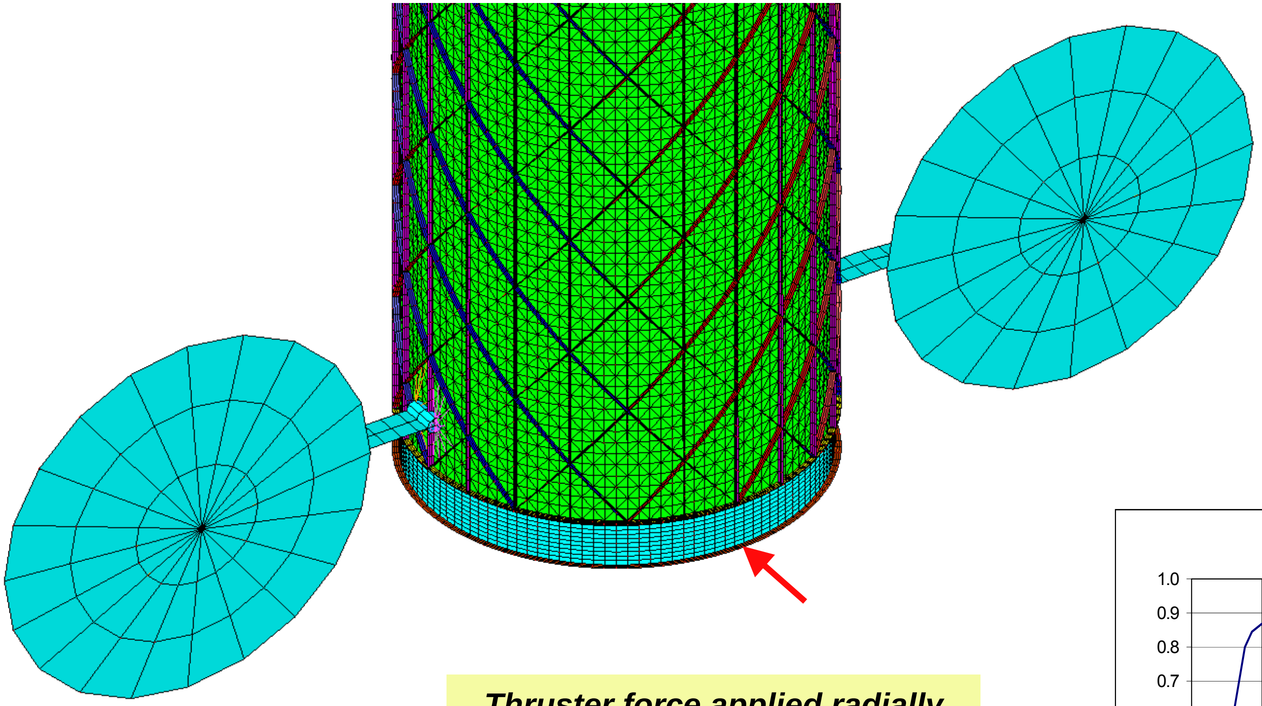
- Stationkeeping once every 21 days
  - After 21 day orbit determination arc (as required by DSN) has been completed
- Pseudo-continuous Solar Pressure offloading
  - Use highly reliable MR103H Aerojet thruster used for Voyager and Cassini; 2 sets of two .9 N thrusters
  - Spaced at +20 and -20 deg azimuths to generate a thrust vector on the sunline, even at roll angles other than zero
  - Max. 0.11 sec burn* every 18 minutes
    - * 0.11 sec calculated for thrust from a single 0.9N Thruster located on the X axis. For the sum of two vectors from thrusters at +20 and -20 deg azimuths, adjust accordingly
  - 300,000 Thruster Firings over 10 Years
    - Voyager had 500,000 burns from single thruster, using same thruster
  - Total amount of monopropellant for 10 years: 25 kg

22N Thrusters Burn Times and Accelerations

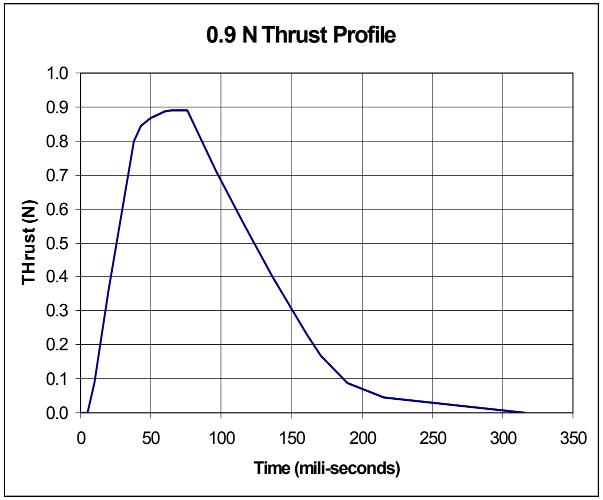
- Largest burn is ELV Dispersion Correction
- Nominal case: 4 ea. 22N Thrusters operating w. zero cosine loss: 88N Thrust force
- Observatory Mass used for calculation: 5930 kg
- Burn time is 2696 sec
  - t = m*v / F >>> 5930kg * 40m/s / 88N = 2696 sec
- Acceleration: 1.5 mili-g
  - a = F/m >>> 88N / 5930kg = 0.015 m/s2

0.9N Thruster Pulse

- **Use highly reliable MR103H Aerojet thruster used for Voyager and Cassini**



Thruster force applied radially inward in anti-sunline direction



Total Impulse = 0.1 N-s

PMD Considerations

- Bidirectional Biprop propellant management devices
- L2 stationkeeping and ΔH maneuvers must be executed within limits of PMD reservoir
- If IXO would be limited by its PMD to thrust in one direction only (as JWST), that would double the ELV Dispersion Correction Delta-V (40 m/s); with bidirectional thrust, this Delta-V line item is 20 m/s

Configuration Considerations

- Mass was the primary driver for the selection of a biprop system over a monoprop one for the baseline configuration
  - A simpler but 70 kg heavier blowdown monoprop system is also viable for the IXO observatory
  - As mass estimates consolidate, the possibility of using a monoprop system will be revisited
- To mitigate ACS thruster lifetime concerns, the same parts, specs, and qualification are used as on Voyager, which has demonstrated 500,000 firings vs. IXO's 10 year total of 300,000. In addition, the perfectly viable contingency option, comparable to JWST's baseline approach, of using the Reaction Wheels to absorb solar torque is also available.
- To mitigate biprop Pressure Regulator lifetime concerns, a trade shall be performed on switching after L2 orbit injection from pressure regulated mode to blowdown mode (a technique used on commercial GEO comm satellites).

Propulsion Parts List w/ Heritage and TRL

Component	Vendor	Model P/N	Lead Times (mo)	Description	Performance Spec	Interfaces	Qty Used (ea.)	Unit Mass (kg)	Total Mass (kg)	Unit Size/ Volume (m)	Unit Cost ($k)	TRL	Heritage
Hz Tank (specific density:1.01 g/cm3)	PSI	80364-1	12	Ti PMD tank 5580 cu.inch (68.04 liter = 68.72 kg propellant)	Op Press 400 psig (27.58 bar)	Transition tube outlet, Ti inlet	2	5.67	11.34	Spherical 22.14 in (562mm)	300	9	INMARSAT-3
NTO Tank (specific density of 1.93 g/cm3)	PSI	80304-1	12	Ti PMD tank 3575 cu.inch (39.13 liter = 75.52 kg propellant)	Op Press 400 psig (27.58 bar)	Transition tube outlet, Ti inlet	2	3.86	7.71	Spherical 19.03 in (483mm)	300	9	SPACENET
He Tank	PSI	80412-1	14	Composite Over-wrapped Pressurant Vessel	Op Press 2,176 psig (150.03 bar)	Ti outlet and inlet'	1	6.99	6.99	12.8''IDx27.5'' Long (325x698.5 mm)	100	9	ETS8 Xenon
22N Hz/NTO Thruster	AMPAC	DST-11H	12	ISP >300 Fee press 80-400 psia	22N (5 lb) Hz/NTO	Ti tube, mounting flange	12	0.74	8.88	10in (25.4cm) long by 3in (7.62cm) dia	90	8	OSC Wild Geese
1N Hz Thruster	Aerojet	MR-103C	8	ISP 224-209s Feed press 400-90 pia (27.6-6.2 bar)	1N (0.2 lbf) Hz, 410,000 pulses	Mounting flanges	2	0.33	1.32	5.82in (14.8cm) x 1.35in (3.4cm) dia	75	9	DS-1, Skynet 4, ADEOS3, MSTI
3/8'', dual coil, LP Latch Valve	Vacco	V1E10362-01	8	5,000 cycle life	300-600 psi (20.7-41.4 bar)	3/8'' Ti, connector	6	0.73	2.90	6.63in (16.8cm) x 2.44in (6.2cm) footprint	30	9	MUSES-C, ASTRO-F, classified
3/8'', dual coil, HP Latch Valve	Vacco	V1E10560-01	8	5,000 cycle life	4500 psia (310 bar) operating pressure	3/8'' Ti, connector	1	0.73	0.73	6.63in (16.8cm) x 2.44in (6.2cm) footprint	30	9	MUSES-C, ASTRO-F, classified
Pyro Valves (NO/NC)	Conax	TBD	8	Zero leak metal seal	Op press varies	Ti tube	12	0.16	1.91	~4in (10.2cm) long	15	9	Atlas, Rosetta, WINDS, many more
Check Valve (dual seat)	Vacco	V0E10495-01	8	1000 operation cycles	Proof 1000 psi (68.9 bar)	Ti tube	2	0.11	0.23	6.4x2.12in (16.3x5.4 cm) footprint	25	9	Many programs, first flew for LM in 1994

Propulsion Parts List w/ Heritage and TRL

Component	Vendor	Model P/N	Lead Times (mo)	Description	Performance Spec	Interfaces	Qty Used (ea.)	Unit Mass (kg)	Total Mass (kg)	Unit Size/ Volume (m)	Unit Cost ($k)	TRL	Heritage
He Regulator (Series Redundant)	Mu	Inlet 5000 to 360 psig	10	Set regulated output press between	Accuracy of +/-2.5% reg outlet pressure	Connector, Ti tube	1	1.25	1.25	2.75in (7cm) x 2.5in (6.4cm) dia	100	9	Mars Odyssey, Mars Orbiter, Cluster II, Messenger
HP Filters (10μ)	Vacco	F1D1028 6-01	9	10 micron filtration	Op press 4200 psig (290 bar)	Ti tube interface	1	0.11	0.11	4.1in (10.4cm) Long, 1.12in (2.8cm) dia.	10	9	HS-601, HS-702, Cassini, Chandra, many other S/C
LP Filters (10μ)	Vacco	F1D1055 9-01	9	10 micron filtration	Op press 400 psig (27.58 bar)	Ti tube interface	4	0.30	1.20	7.85in (19.9cm) Long 1.75in (4.3cm) dia	10	9	HS-601, HS-702, Cassini, Chandra, many other S/C
Fill/Drain Valves	Vacco	TBD	9	Load fuel and pressurant as well as test ports	3 seals	Ti tube interface, mounting flanges	11	0.11	1.25	~5 in (12.7cm) long by ~1in (2.54cm) dia	10	9	Many flight programs
Pressure Transducer	Tabor	TBD	10	Reads in voltage the pressure of the tanks	Ranges 0-580 psia (0-40 bar) and 1-4200 psia (0-280 bar)	Ti tube, Connector	5	0.27	1.36	~6 in (15.24cm) long by ~1in (2.54cm) dia	15	9	X-34, ASTRIUM, NEXT
Venturi Orifices	Fox	TBD	4	Eliminate effects of water hammer	As needed	Ti	4	0.05	0.20	3/8'' dia x 1''	2	9	SDO, LRO, many other S/C
Manifold, etc.	TBD	TBD	3	Tubes, manifold stands, etc	As needed	Varies	1	6.81	6.81	TBD	100	9	Many S/C
							TOTAL MASS		**53.96**		**$3.5M**	**TOTAL COST**	

Total Mass is the total DRY mass, propellant not included.

Cost does not include spares or NRE.

Electrical Power System

Summary

EPS Sizing: Sized for 10 years

Total Output: 6600 W CBE BOL max, 5200 W CBE EOL min (10 yrs - 20% decay)

Solar Arrays: UltraFlex Solar Arrays total (272 w/m2 per ATK): 3400 W CBE (BOL)

- Total S/A area populated by solar cells: 12.5 m^2
- *Total area available : 18 m^2*

Body mounted array: 3200 W CBE (BOL)

- Total surface area: 13.5 m^2

Battery: 2800 Wh (100 Ah) LiIon battery

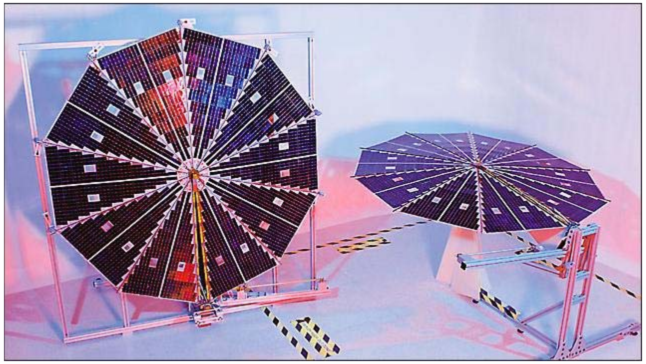
- Cell by-pass switches, w/ trickle charger

Instruments and S/C: 28 VDC regulated PSE power

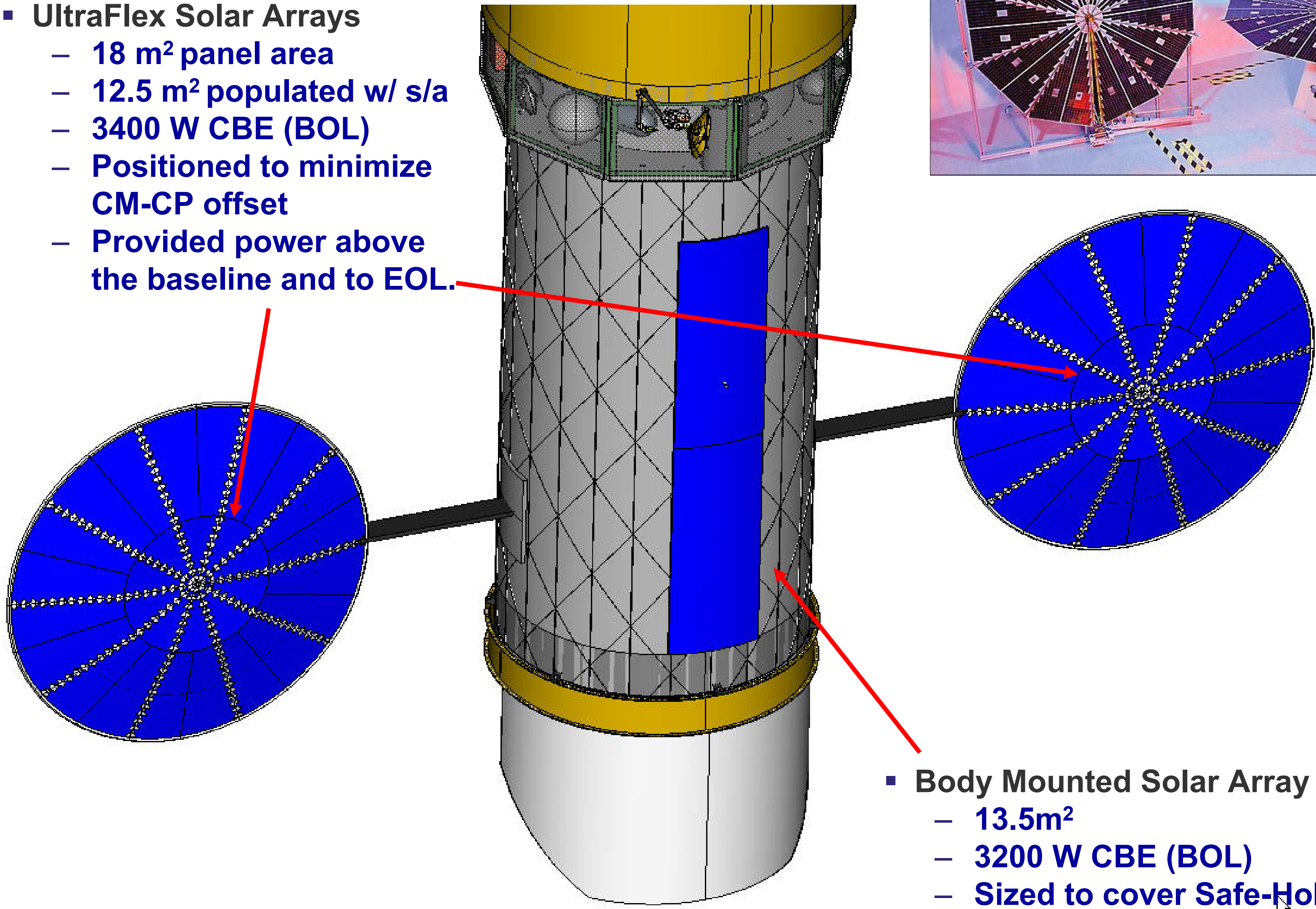
FMA Thermal: Unregulated power from EPS bus

- Body mounted array to provide baseline (constant peak power) and run full on at all times from begging of life (BOL) to end of life (EOL).

S / A Layout

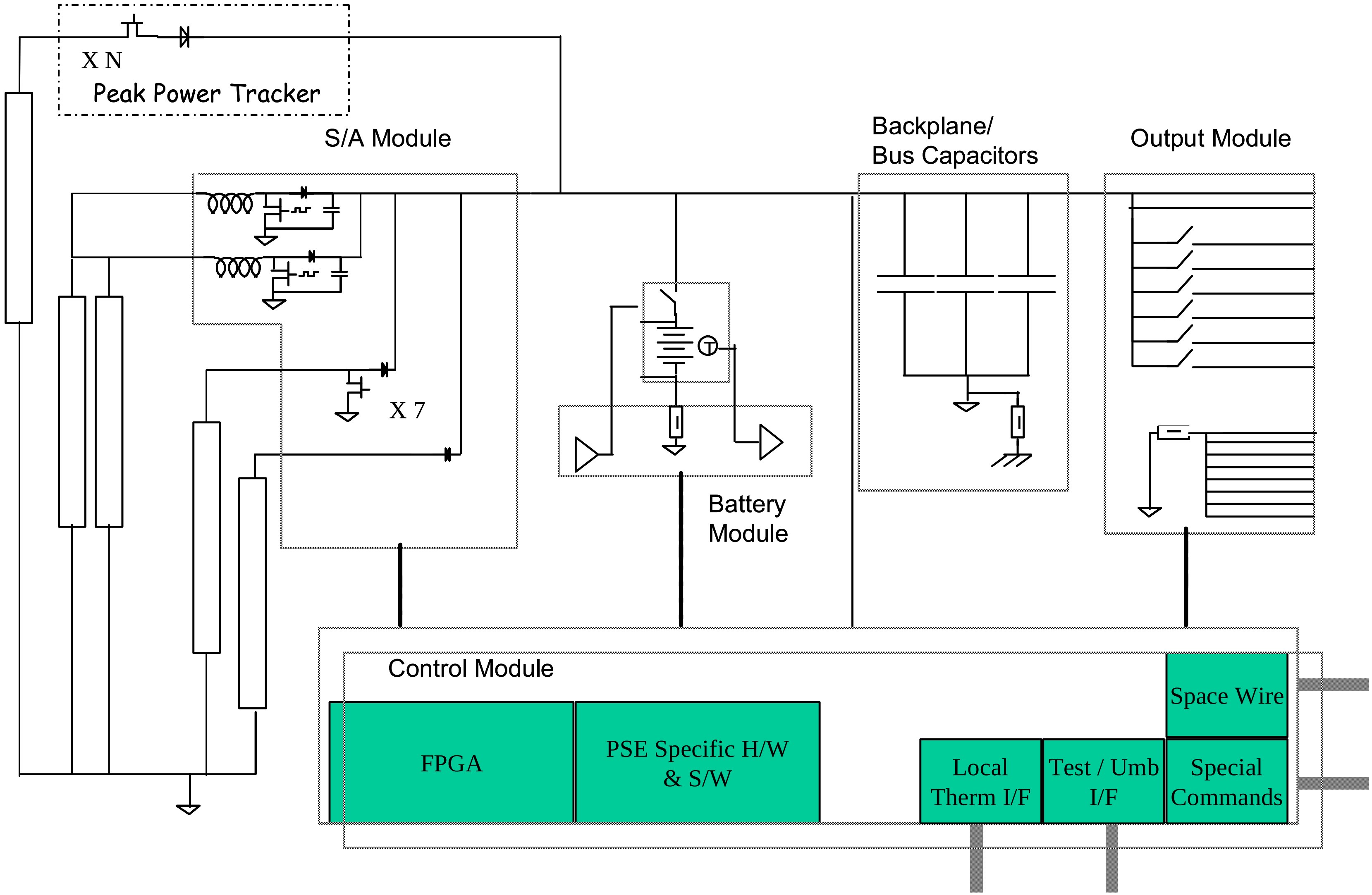


- UltraFlex Solar Arrays
  - 18 m^2 panel area
  - 12.5 m^2 populated w/ s/a
  - 3400 W CBE (BOL)
  - Positioned to minimize CM-CP offset
  - Provided power above the baseline and to EOL.



- Body Mounted Solar Array
  - 13.5m^2
  - 3200 W CBE (BOL)
  - Sized to cover Safe-Hold Mode
  - Provides Baseline constant power

EPS Electrical Block Diagram



Observatory Level Power Loads

Max. Exp. Value (CBE + 30%)	Launch	Cruise	Science	Downlink	Slew	Safehold	Max
Observatory	508	3620	3648	3681	2338	3102	4777
S/C	144	1169	1197	1229	1571	1836	2016
Payload	364	2452	2452	2452	2452	1265	2762

S/C *Max. Exp. Values (CBE +30%)*

	Launch	Cruise	Science	Downlink	Slew	Safehold	Max
S/C Total	144	1169	1197	1229	1571	1836	2016
ACS	16	65	70	70	433	57	569
C&DH	98	192	192	203	205	185	229
RF Comm	26	57	57	104	57	57	117
Mech	0	2.4	2.4	2.4	2.4	2.4	2.4
Propulsion	0	7	7	7	13	7	7
Power	5	185	217	219	210	175	305
Harness	0	23	27	27	26	22	38
Thermal	0	637	624	598	624	1332	749

Payload *Max. Exp. Values (CBE +30%)*

	Mode 1	Mode 2	Mode 3	Mode 3	Max
Payload Total	2452	2338	2087	2156	2762
FMA	1456	1456	1456	1456	1456
XMS	844	420	420	420	844
WFI	33	289	33	33	289
HXI	6	60	6	7	60
XGS	100	100	100	100	100
XPOL	0	0	60	0	0
HTRS	13	13	13	141	13

Unit Powers *Max. Exp. Values (CBE +30%)*

	Ave	Standby	Safehold	Launch	Peak
Payload Total	2950	1924	1265	364	
FMA	1456	1456	1265	364	1456
XMS	844	420	0	0	914
WFI	289	33	0	0	340
HXI	60	6	0	0	60
XGS	100	0	0	0	107
XPOL	60	0	0	0	60
HTRS	141	10	0	0	141

EPS Configuration Overview – Solar Arrays

- Body mounted solar array
  - $13.5\ m^2$ body mounted solar array: 3200 W CBE (BOL)
  - All survival heaters wired exclusively to Body Mounted Array
    - Allows for Observatory Safe-Mode of indefinite duration even right after LV separation (before deploying Ultraflex arrays)
  - All FMA Heaters also wired to Body Mounted array, but bypassing regulators (see "FMA Temp Control Electrical Block Diagram" slide)
  - During normal mission modes, the body mounted strings will provide their max capacity power to the bus. This provides as constant thermal load on the shell of the spacecraft as possible.

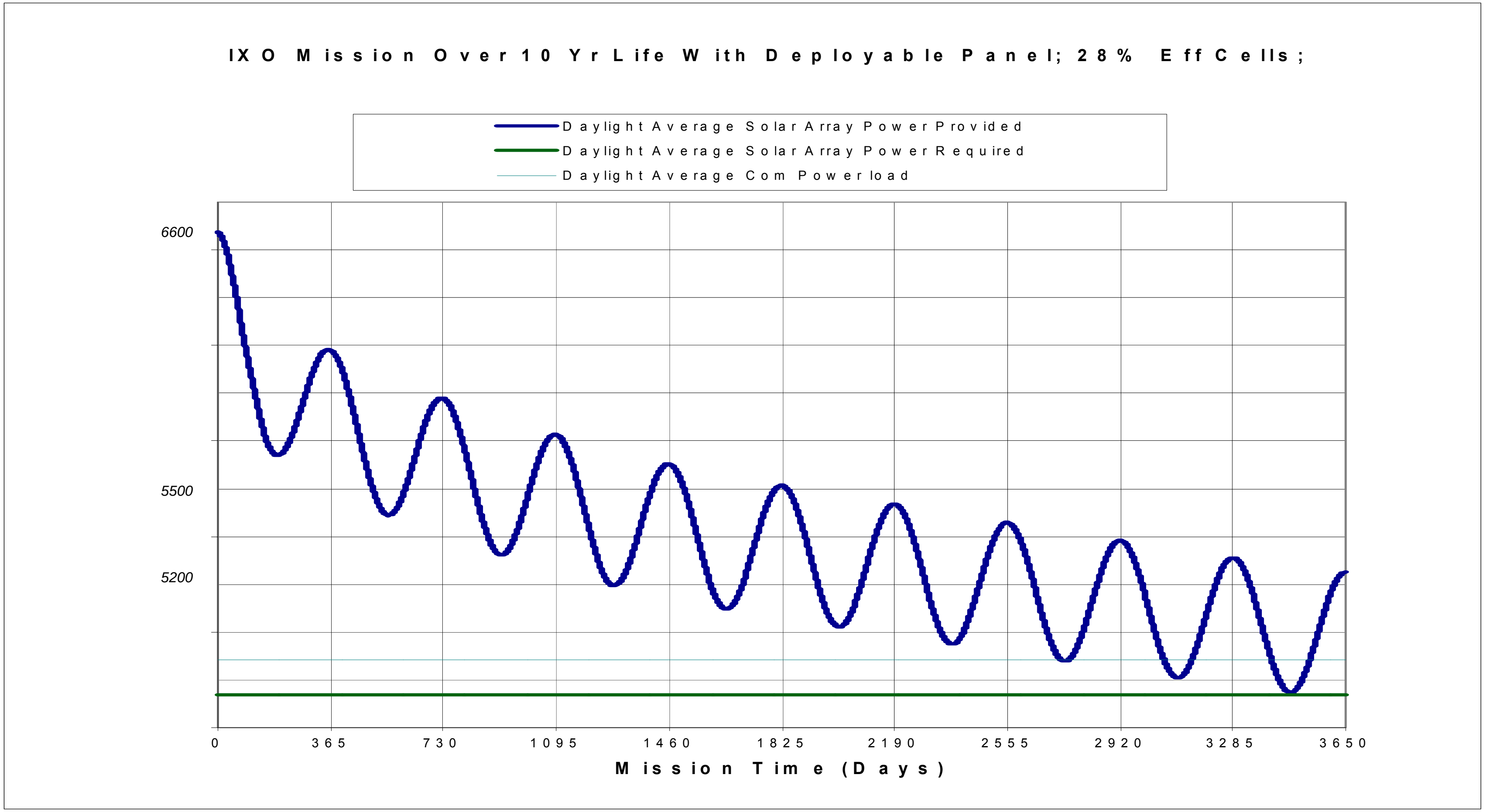
- Two UltraFlex solar arrays contribute to main Observatory power
  - 2 ea $6.25\ m^2$ Solar Arrays for $12.5\ m^2$ total area (at 272 W/m^2 per ATK); 3400 W CBE (BOL)
    - Arrays total wing size about 3.4 m diameter (9.0 m2 per wing)
    - Only partially populated w/ cells, rest of the area used as a Solar Sail to minimize CM-CP offset
    - Array mounts positioned on Fixed Metering Structure
  - S/A output routed to PSE, regulated to 28VDC to power Observatory
  - The UltraFlex arrays will provide the difference between the load demand and the capability of the Body Mounted solar array.
    - This array will make up the difference as the spacecraft goes to end of life (EOL) both to compensate for the degradation of the body mounted array and for any increase in thermal FMA EOL power increases.

Ultraflex Array Properties

	BOL Values
Specific power	***156 W/kg***
Power / unit area	272 W/m^2
Area density	1.75 kg/m^2

- **Configuration:**
  - **Wing size 3.4 m diameter (7.0 m^2 per wing)**
  - **Array weight**
    - **Two wings fully populated w/ 18 m^2 of s/a's would weigh 29.3 kg (assumes "typ." launch loads)**
    - **Two wings partially populated w/ 12.5 m^2 of s/a's weigh 27.4 kg**
- **XTJ GaInP2/GaAs/Ge solar cells, 110 micron thick**
  - **29.3% min. average cell efficiency**
  - **String length: 16 cells; 80 strings per wing; 1280 cells per wing**
  - **Net string voltage, BOL: 30.5 Volts (for >28V EOL)**
  - **Voc 2.655 V; Jsc 18.10 mA/cm2; Vmp 2.33 V; Jmp 17.45 mA/cm^2;**
  - **Fill Factor 84.5%**
  - **4-mil CMG covers**

Typical L2 10 Year Decay of S/A Output



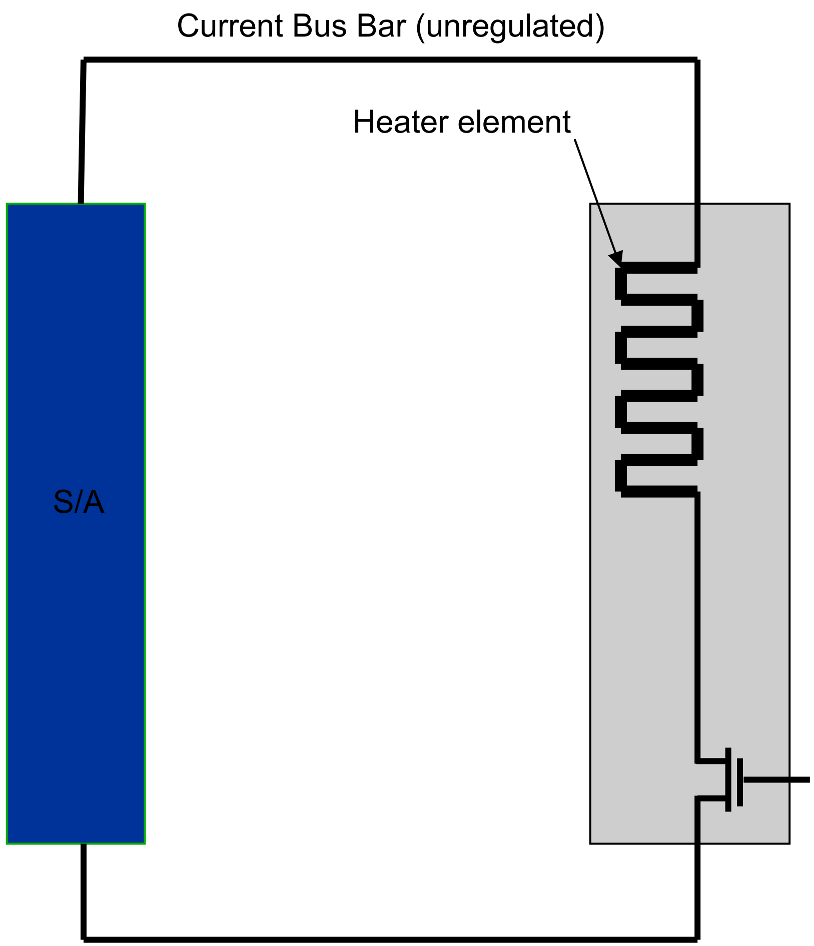
EPS Configuration Overview – Batteries, PSE

- 2800 Wh Battery sized to carry observatory safe-hold mode for almost an hour even without sun
  - Batteries are only needed at launch
  - After launch, barring completely unforeseen events, batteries are not needed since the solar arrays continuously point at the sun
- No independent Power System Electronics, PSE functions provided by the C&DH Subsystem
  - Management of the Main Power System is provided by the C&DH
  - Fore and Aft RIU’s distribute power to payload
  - Battery charging control implemented as FPGA

Simple Independent Unregulated Power System for FMA Temperature Control

- The FMA Temperature Controller has independent unregulated power system
  - About half of the strings on the body mounted array are dedicated to the FMA and are routed directly to the FMA Temperature Controller
- FMA Temperature Controller regulates directly to Temperature regardless of voltage or current
  - Regulator uses basicaly a single FET
  - Every Watt dissipated in the FETs is used: FETs are also mounted on the Pre-Collimator Blades

FMA Temperature Control Power Circuit

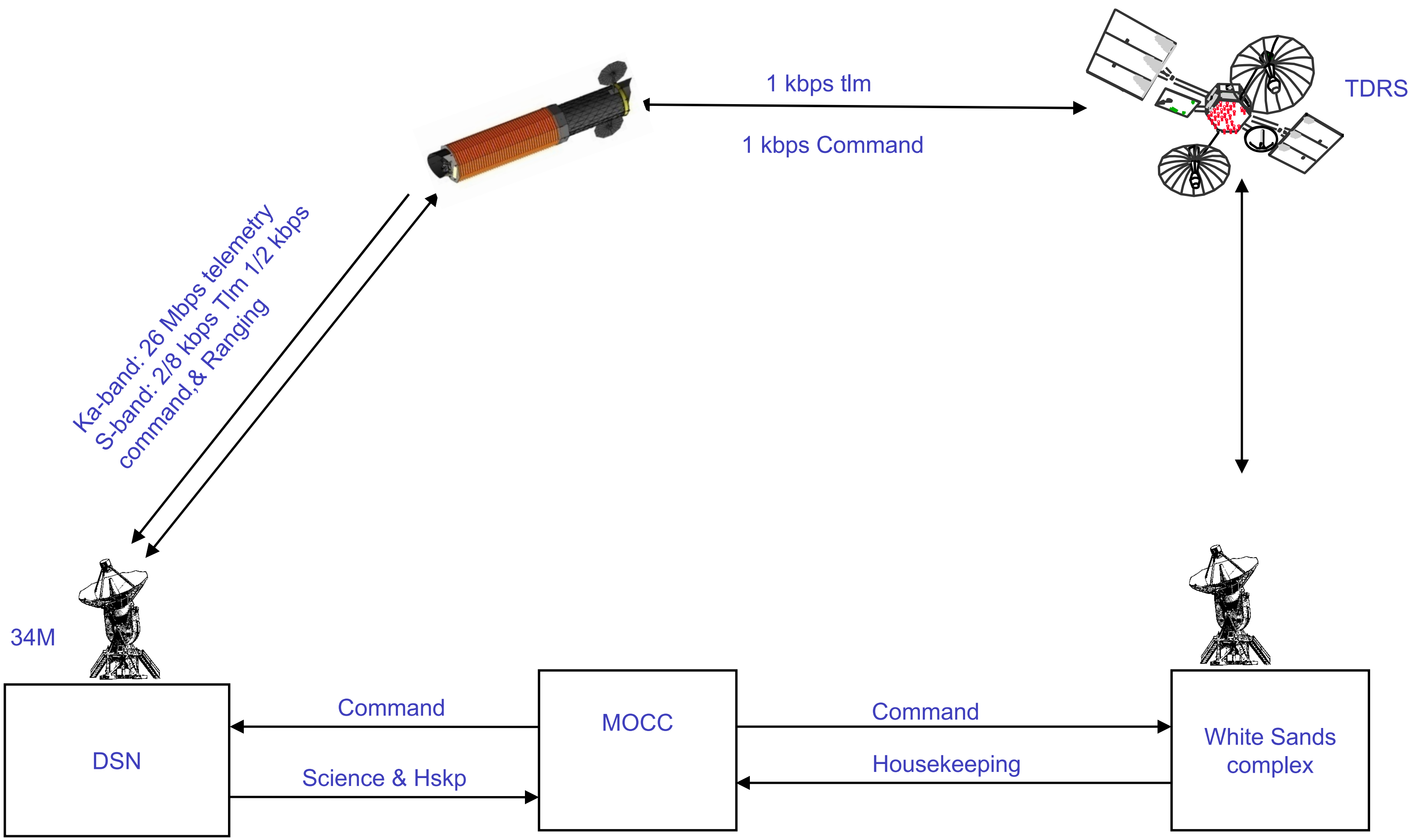


RF Comm

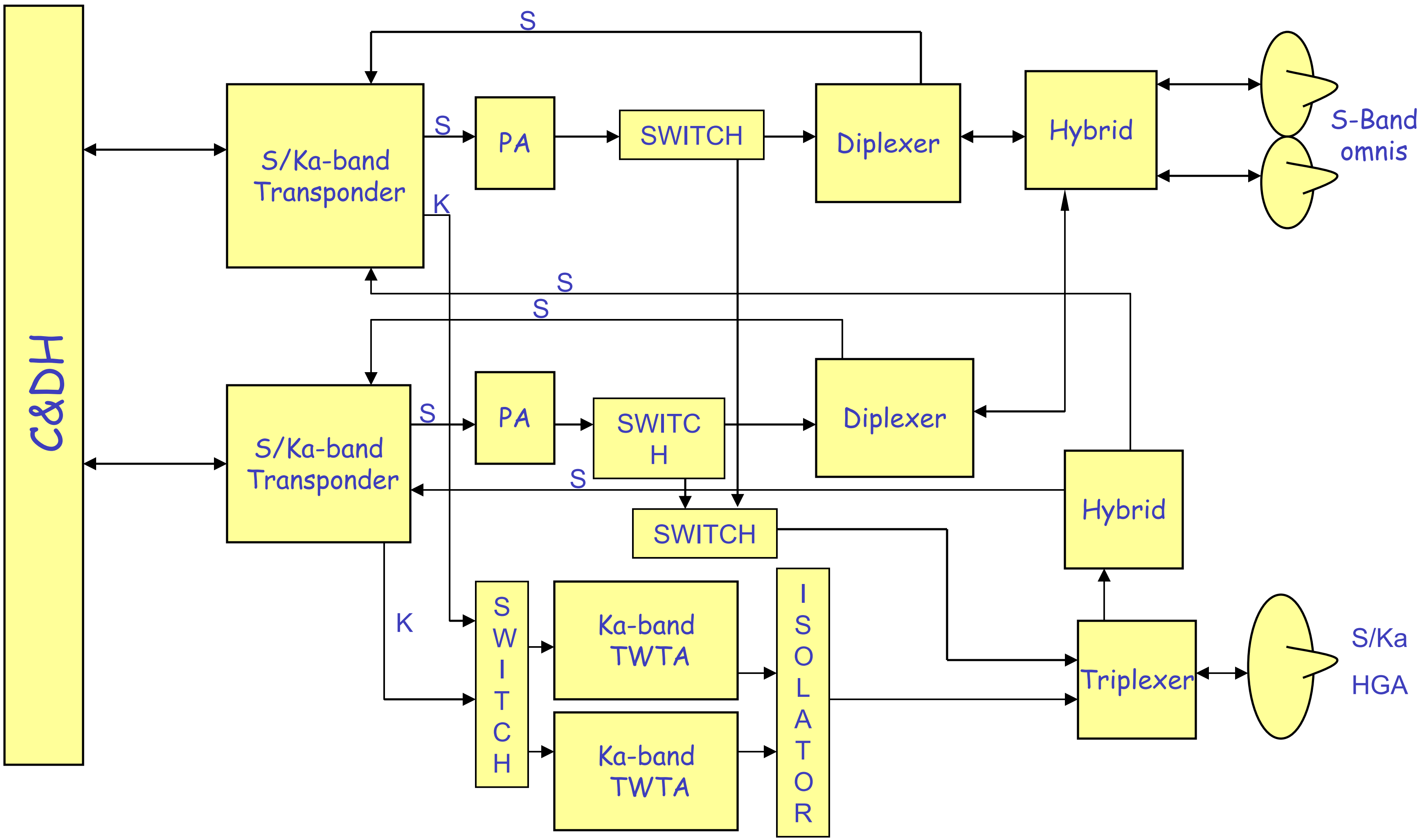
Overview

- Ka-Band for science and data dumps via 0.7 m HGA to DSN 34 meter
  - Data dumps at 26 Mbps
  - One 30 minute DSN contact / day required during science phase of mission, two 30 min DSN contact / day during cruise to L2 (for OD), and continuous DSN contact during initial 4 weeks commissioning phase
- S-Band TT&C via 0.7 m HGA to DSN 34 meter
  - 2 kbps command / 8 kbps telemetry
- S-Band TT&C via omni to DSN 34 meter
  - 1 kbps command
  - 2 kbps telemetry
- Ranging for orbit determination
- S-Band thru TDRSS for launch and LEO critical events
  - 1 kbps command
  - 1 kbps telemetry
- CCSDS
- Reed-Solomon encoding

Functional Configuration



Block Diagram



Link Margin Summary

Link	Data Rate	Margin (db) Max range	Comment
Ka-Band Downlink	26 Mbps	+3.5 +>5 at GDS	0.7M HGA to 34M 10 deg at CAN
S-Band Downlink	8 kbps	+17.6	HGA to 34M
S-Band Uplink	2 kbps	+14.1	34M to HGA 200 watts
S-Band Uplink	1 kbps	+2.5	34M to OMNI 2 kw
S-Band Downlink	2 kbps	+3.7	OMNI to 34M
S-Band Return	1 kbps	+2.5	OMNI to TDRSS within the nominal TDRSS envelope
S-Band Forward	1 kbps	+0.6	TDRSS to OMNI within the nominal TDRSS envelope
Ranging		positive	Via DSN

TDRSS guarantees support with a margin of >0 dB

Component Summary

Component	DC Power (watts) pk/avg	Mass (kg)
S/Ka Transponder (2) *	30/26	6.2
S/Ka Antenna (0.7 Meter) incl. Gimbal Assy	30/2	8.5
10 watt Ka TWTA (2)	30/22	7
5 watt S-band PA (2)	20/2	1
S-band omni (2)	--	2
Diplexer (2)	--	1.2
Triplexer	--	1
Hybrids (2)	--	0.4
Switches (4)	--	1
Isolator and cabling, misc	--	3
TOTALS	110/52	31.3

* This Transponder does not exist, but could be developed from the X/Ka SDST with NRE.

Separate S-band transponders and Ka-band transmitters that exist could be used but with additional weight of ~7 kg. NRE costs would have to be compared with the cost of separate units

DSN Support

- Launch / Early Orbit, and Initial 4 weeks commissioning phase
  - Continuous DSN contact baselined for initial month of the mission
  - Near continuous tracking (range & doppler) required for first 48 hours to plan for and reconstruct dispersion correction maneuver (planned for L+24 hours)
- Transfer orbit
  - Two 30 minute contacts/day
  - 24 hour support before and after each mid course corrections (Two corrections planned)
  - 100 days to orbit
- At L2
  - 30 minutes of ranging and doppler every day
  - Alternating northern and southern hemisphere station contacts
    - This scenario requires the spacecraft to limit its momentum unloads to no more often than once every two days
  - Twice a month a 3 hour contact (for peak rate data)
- Use DSN 34 M antenna
- Pre-pass time: 45 minutes
- Post-pass time: 15 minutes

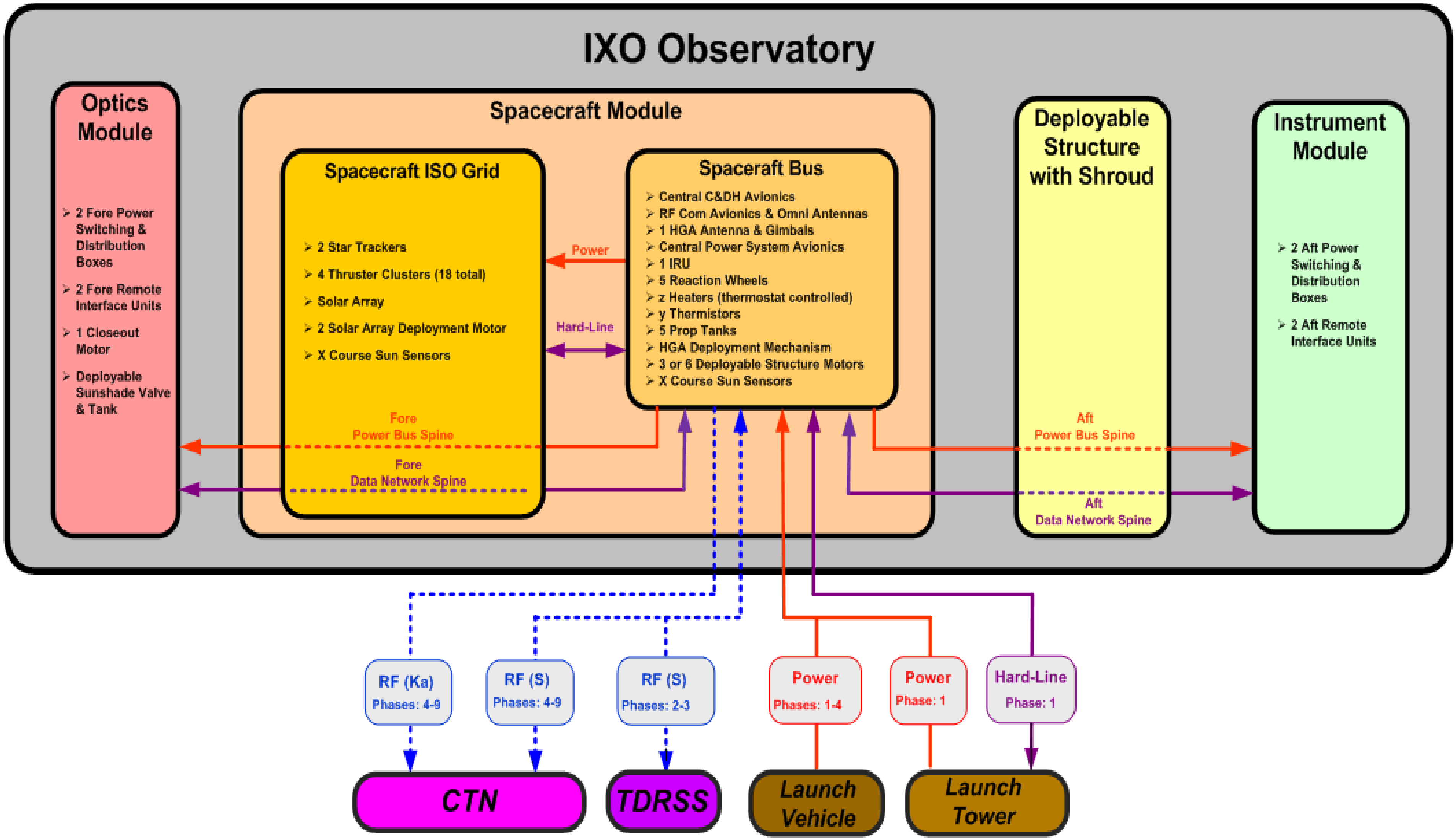
Avionics

IXO Avionics System Overview

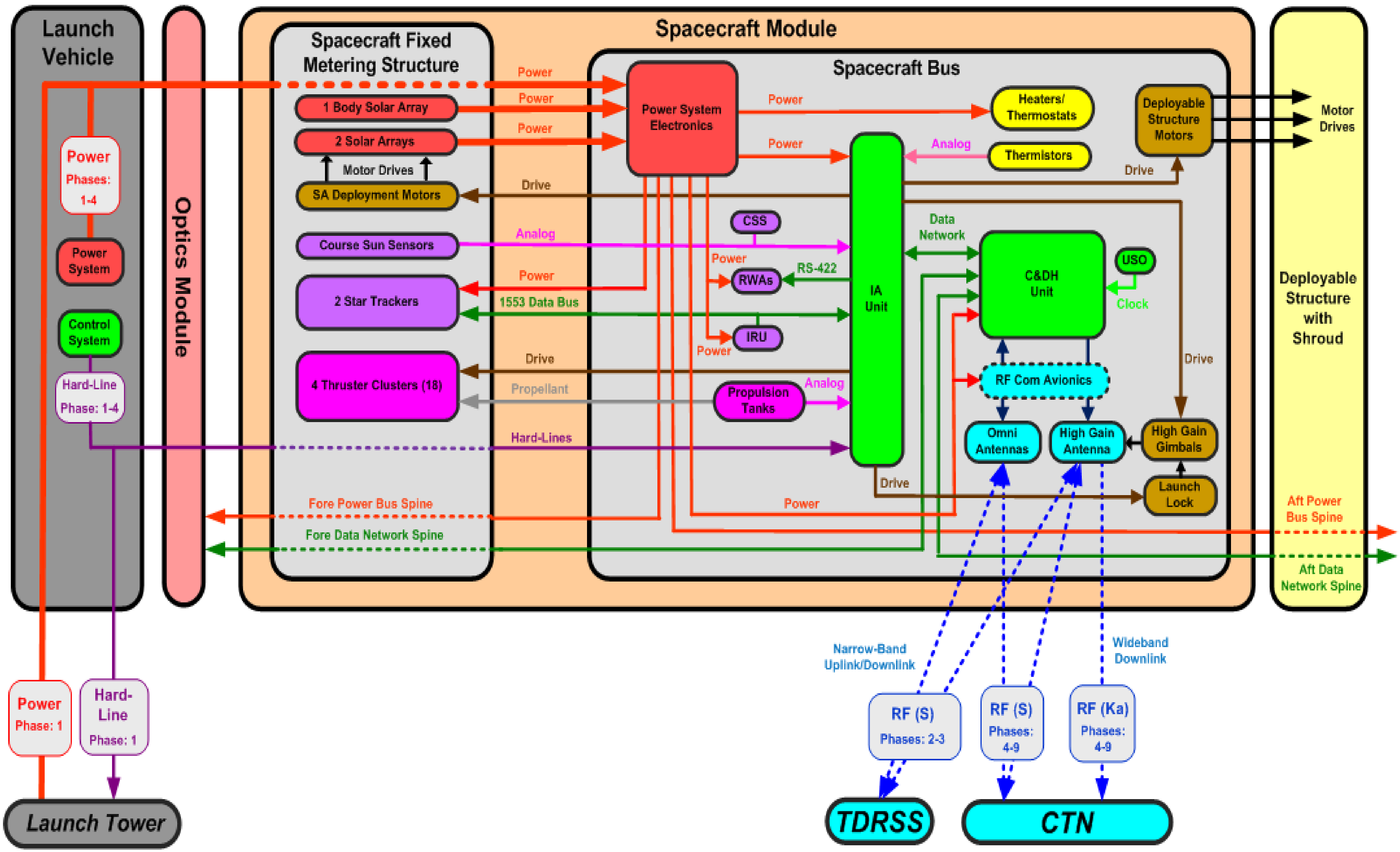
- The IXO Avionics System utilizes a distributed architecture with minimal interfaces between the Spacecraft Module and the two end modules: Optics Module & Instrument Module. This architectural approach minimizes wiring harness mass, which is the heaviest part of an avionics system. It also minimizes development and I&T costs due to its highly modular design and simple interfaces.

	Sub-Systems	LRUs	Functions	LRU Sizes (cm) H x D x L	Mass (kg)	Power (W)
Optics Module	C&DH	RIU	▪ Power Switching/Distribution ▪ Master Control & Monitoring	24.5 x 25.0 x 17.2	12.2	12
Spacecraft Fixed Metering Structure						
Spacecraft Bus	C&DH	C&DH Unit IA Unit USO	▪ Baseband Telecom ▪ Network Master ▪ Spacecraft Computer ▪ Sensor/Effector Interface ▪ Observatory Clock	24.5 x 25.0 x 29.4 24.5 x 25.0 x 23.3 4.0 x 4.0 x 10.0	15.3 19.3 0.5	55 35 3
Deployable Structure						
Instrument Module	C&DH	RIU	▪ Power Switching/Distribution ▪ Master Control & Monitoring	24.5 x 25.0 x 20.2	14.2	17
Observatory Totals					**61.5**	**122**

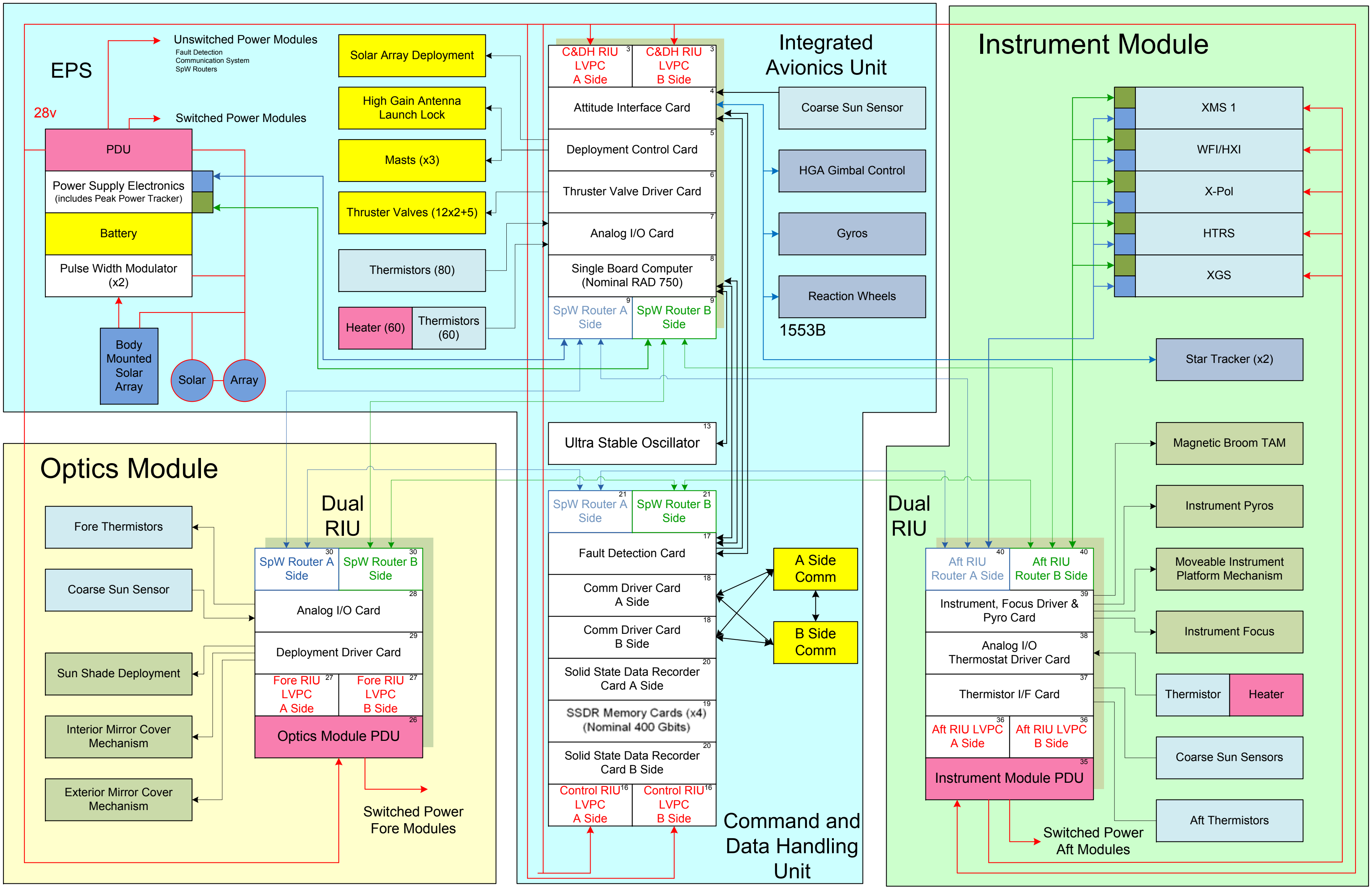
Level-2 Design: Module Functions



Level-3 Design: Avionic System Diagram



Level-4 Design: Sub-Assemblies & Circuit Card Assemblies



Technologies and Building Blocks

- All technologies used for the implementation of the avionics architecture is currently at TRL-6
- The following key technologies were employed:
  - BAE RAD 750 Single Board Computer (6U)
  - 0.5 Gbit SDRAM Memory Parts
  - Spacewire Data Network Interface, VHDL, and LVDS

IXO Avionics Mass Power and Size Summary

Unit	Mass (kg)
Integrated Avionics Unit	19.3
Ultra Stable Oscillator	0.5
Command and Data Handling Unit	15.3
Optics Module RIU	12.2
Instrument Module RIU	14.2
Total	61.5

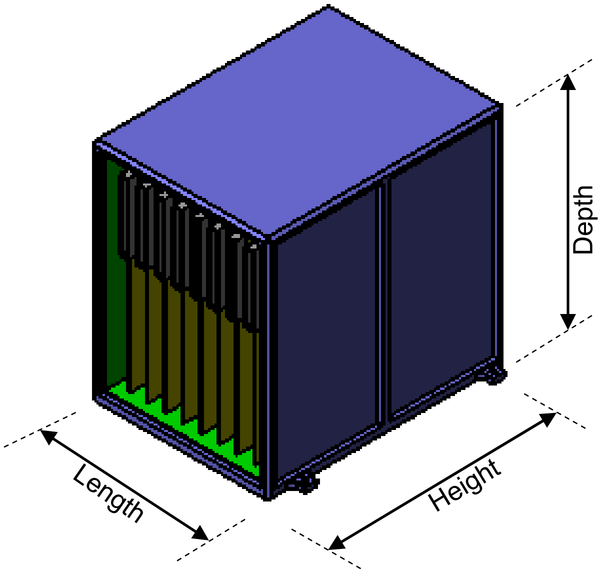
Unit	Power (W)
Integrated Avionics Unit	35.0
Ultra Stable Oscillator	3.0
Command and Data Handling Unit	55.0
Optics Module RIU	12.0
Instrument Module RIU	17.0
Total	122.0

Unit	H	D	L
Integrated Avionics Unit	245	250	233
Ultra Stable Oscillator	100	100	100
Command and Data Handling Unit	245	250	294
Optics Module RIU	245	250	172
Instrument Module RIU	245	250	202

Integrated Avionics Unit Mass and Size

Integrated Avionics Mass/Size Calculator

Number of C&DH Cards not including FD&R	6	
Fault Detection and Recovery	no	
Strings (1-single, 2-dual, …)	2	
Integrated RIU (yes/no)	no	
Number of RIU cards	0	
Form factor (3u/6u)	6u	
Card Heigth (160/220)	220 mm	
Wall thickness	100 mills	
Partition Thickness	100 mills	
Card Slot Width (0.8in.=20.32mm or 1.2in.=30.48mm)	30.48 mm	
Height	245 mm	9.65
Depth	250 mm	9.84
Length Backplane	208 mm	8.18
Length Chassis	233 mm	9.17
Chassis Mass	4.58 kg	10.10
Card Mass	13.00 kg	28.67
Backplane	1.75 kg	3.86
Total Mass	19.33 kg	42.62 lbs.



V1.1.4

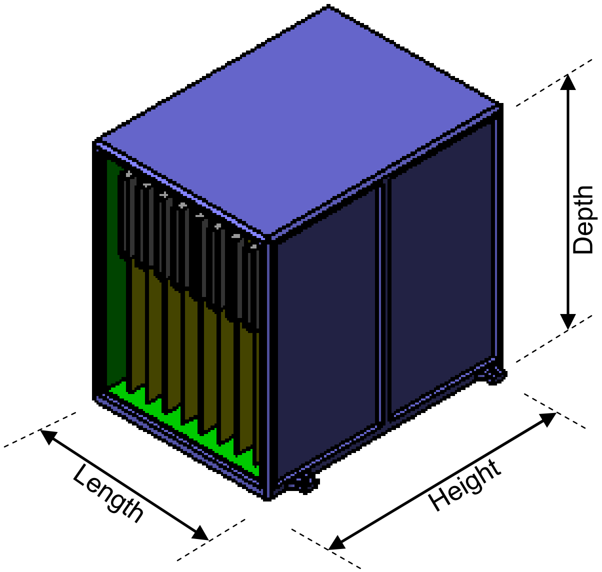
Integrated Avionics Unit Cards and Power Consumption

Component	Ident	Number	Launch	Science	Safe	Peak
Low Voltage Power Converter	3	1	7	9	9	24
Attitude Interface Card	4	2	0	7	7	7
Deployment Control Card	5	2	0	0	0	30
Thruster Valve Drive Card	6	4	0	0	0	30
Analog I/O Card	7	2	4	4	4	4
RAD 750 SBC	8	2	11	11	11	11
SpaceWire Router	9	1	4	4	4	4
Harness	10	1	0	0	0	0
Chassis	11	1	0	0	0	0
Total			26	35	35	110

Optics Module (Fore) RIU Mass and Size

Fore RIU Mass/Size Calculator

Number of C&DH Cards not including FD&R	7	
Fault Detection and Recovery	yes	
Strings (1-single, 2-dual, …)	2	
Integrated RIU (yes/no)	no	
Number of RIU cards	0	
Form factor (3u/6u)	6u	
Card Heigth (160/220)	220 mm	
Wall thickness	100 mills	
Partition Thickness	100 mills	
Card Slot Width (0.8in.=20.32mm or 1.2in.=30.48mm)	30.48 mm	
Height	245 mm	9.65 in.
Depth	250 mm	9.84 in.
Length Backplane	269 mm	10.58 in.
Length Chassis	294 mm	11.57 in.
Chassis Mass	3.63 kg	8.00 lbs
Card Mass	8.40 kg	18.52 lbs
Backplane	0.20 kg	0.44 lbs
Total Mass	12.23 kg	26.97 lbs



V1.1.4

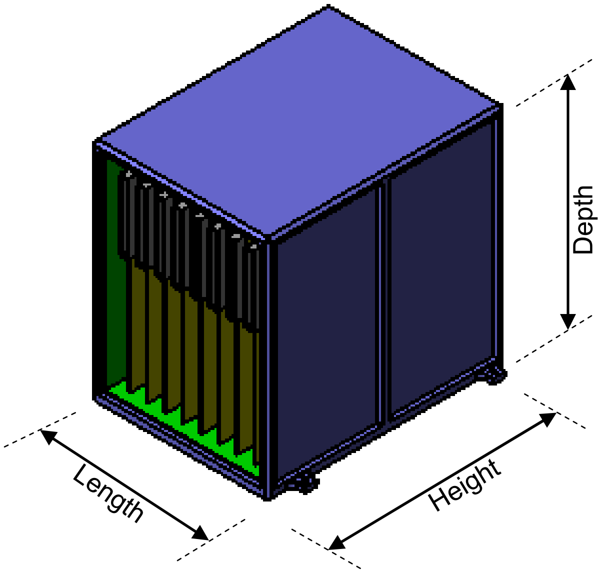
Optics Module (Fore) Cards and Power Consumption

Component	Ident	Number	Launch	Science	Safe	Peak
Optic Module PDU	26	1	0	0	0	1
Low Voltage Power Converter	27	1	4	4	4	12
Analog I/O Card	28	2	4	4	4	4
Deployment Control Card	29	2	0	0	0	30
SpaceWire Router	30	1	4	4	4	4
Harness	31	1	0	0	0	0
Chassis	32	1	0	0	0	0
Total			12	12	12	50

Instrument Module (Aft) RIU Mass and Size

Aft RIU Mass/Size Calculator

Number of C&DH Cards not including FD&R	4		
Fault Detection and Recovery	yes		
Strings (1-single, 2-dual, …)	2		
Integrated RIU (yes/no)	no		
Number of RIU cards	0		
Form factor (3u/6u)	6u		
Card Heigth (160/220)	220	mm	
Wall thickness	100	mills	
Partition Thickness	100	mills	
Card Slot Width (0.8in.=20.32mm or 1.2in.=30.48mm)	30.48	mm	
Height	245	mm	9.65
Depth	250	mm	9.84
Length Backplane	177	mm	6.98
Length Chassis	202	mm	7.97
Chassis Mass	3.95	kg	8.71
Card Mass	10.00	kg	22.05
Backplane	0.25	kg	0.55 lbs.
Total Mass	14.20	kg	31.31 lbs.



V1.1.4

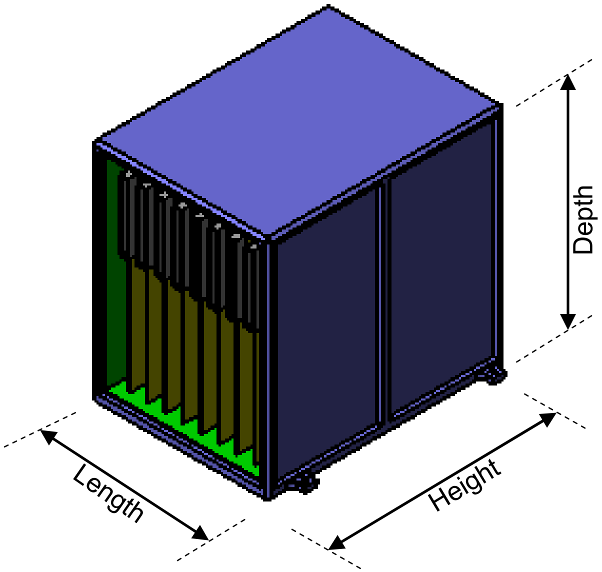
Instrument Module (Aft) Cards and Power Consumption

Component	Ident	Number	Launch	Science	Safe	Peak
Instrument Module PDU	35	1	0	0	0	1
Low Voltage Power Converter	36	1	5	5	5	5
Focus Driver	37	2	0	0	0	15
Analog I/O Card	38	2	4	4	4	4
Analog I/O Card	39	2	4	4	4	4
SpaceWire Router	40	1	4	4	4	4
Harness	41	1	0	0	0	0
Chassis	42	1	0	0	0	0
Total			17	17	17	32

Command and Data Handling Unit Mass and Size

C&DH Mass/Size Calculator

Number of C&DH Cards not including FD&R	8	
Fault Detection and Recovery	no	
Strings (1-single, 2-dual, …)	1	
Integrated RIU (yes/no)	no	
Number of RIU cards	0	
Form factor (3u/6u)	6u	
Card Heigth (160/220)	220 mm	
Wall thickness	100 mills	
Partition Thickness	100 mills	
Card Slot Width (0.8in.=20.32mm or 1.2in.=30.48mm)	30.48 mm	
Height	245 mm	9.65 in.
Depth	250 mm	9.84 in.
Length Backplane	269 mm	10.58 in.
Length Chassis	294 mm	11.57 in.
Chassis Mass	5.17 kg	11.40 lbs
Card Mass	9.80 kg	21.61 lbs
Backplane	0.28 kg	0.62 lbs
Total Mass	15.25 kg	33.63 lbs.



V1.1.4

Command and Data Handling Cards and Power Consumption

Component	Ident	Number	Launch	Science	Safe	Peak
Low Voltage Power Converter	16	1	12	12	12	12
Fault Detection and Recovery	17	1	3	3	3	3
Comm Driver Card	18	2	10	10	10	10
Memory	19	3	20	20	20	20
Solid State Data Recorder Card	20	2	6	6	6	6
Spacewire router	21	1	4	4	4	4
Harness	22	1	0	0	0	0
Chassis	23	1	0	0	0	0
Total			55	55	55	55

FSW

Requirements and Assumptions

- Payload support
  - Instrument packages are responsible for any data compression
  - Instrument packages are responsible for CCSDS packetization and time stamping of science data
  - C&DH/FSW provides commands/time distribution, accepts HK and science data
  - C&DH/FSW provides active thermal control for Flight Mirror Assembly (FMA)
  - C&DH/FSW provides command and control for instrument focus and rotating platform mechanism
- No Independent Attitude Control Electronics (ACE) CPU
  - Safehold control software will reside in the main processor
    - Processor-free survival safe mode implemented in the Attitude Interface Card
  - Spacecraft sun avoidance for mirror and detector decks
- No independent Power System Electronics (PSE) CPU
  - Management of the Main Power System will be part of the C&DH FSW
  - Battery charging control implemented as FPGA in the PSE
- Command & Data Handling including hardware command decryption. FSW to provide decryption key management
- High level of onboard autonomy
- Gimbaled High Gain Antenna, Fixed Solar Array
- No FSW end of mission requirements
- FSW development using ASIST for T&C GSE

FSW - C&DH Software Functionality

- Mission Specific Functions
  - Uplink/downlink management including command decryption key management
  - Failure Detection and Correction Management
  - Deployables Management
  - S/C Power Switched Services Management
  - Thermal control, payload Support
  - Time Management and Distribution

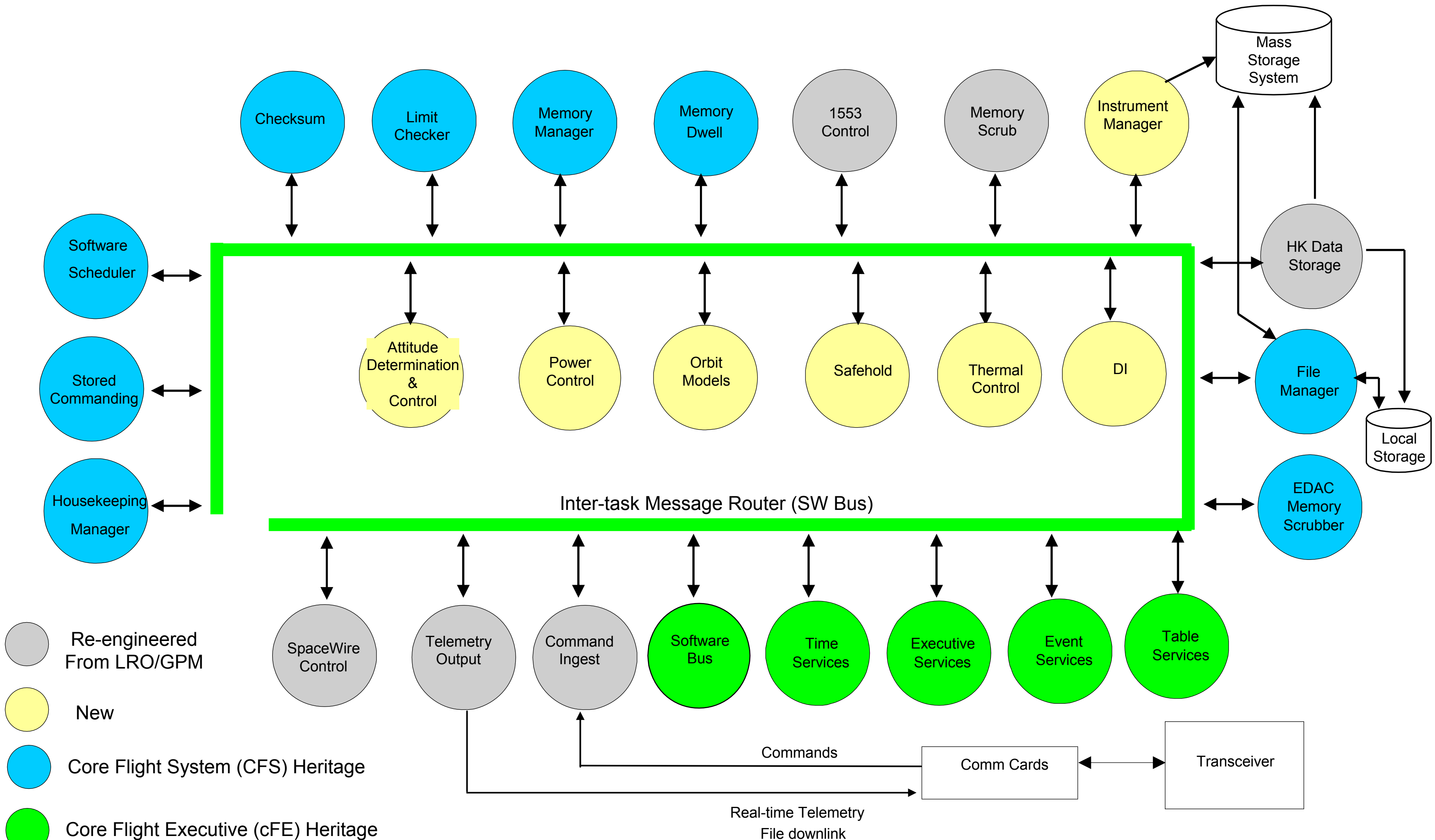
- Generic Features
  - Commercial real-time executive to provide multi-tasking, scheduling, intertask communication, interrupt and exception handling
  - Capability to perform hardware initialization
  - Bootstrap loader to provide basic DRAM and EEPROM memory loads and dumps capabilities
  - Provide in-flight capability to modify (patch) flight software
  - Command and data handling shall comply with the CCSDS definitions
  - Collection and distribution of on-board housekeeping data
  - S/C and payload commands distribution & management
  - Onboard autonomy
    - Absolute & relative time-tagged command sequences
    - Limit checker
  - Health & Safety Management
    - Memory Checksum Management
    - EDAC Memory Scrub Management
    - Parameter Table & Memory Management

FSW - ACS Software Functionality

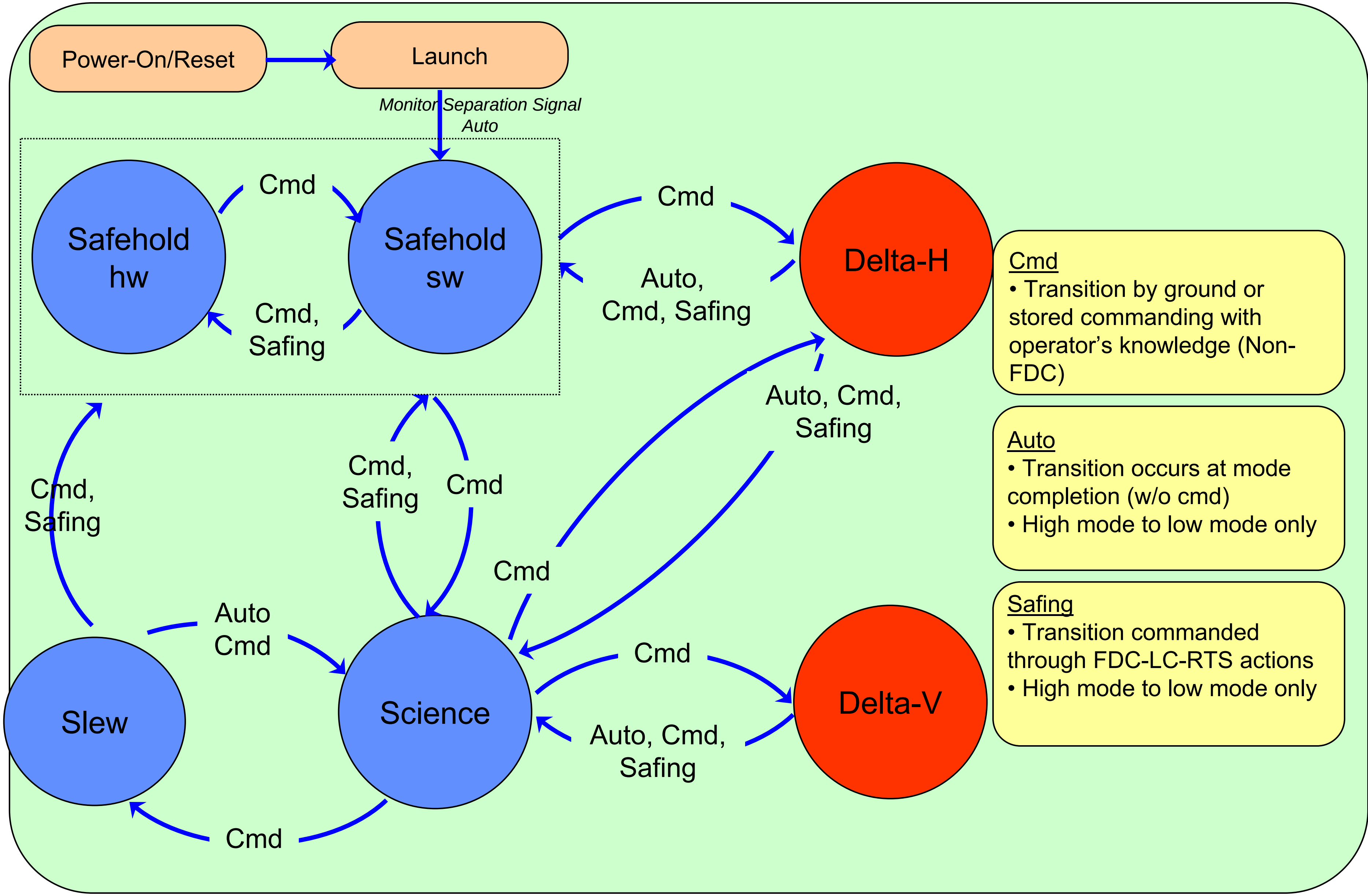
- Mission Specific Functions
  - Kalman Filtering
  - Process sensor and actuator data
    - Course Sun Sensors
    - Inertial Measurement Unit
    - Star Trackers
    - Reaction Wheels
    - Thrusters
  - Attitude determination
  - Manage and execute control modes
    - Cruise
    - Science
    - Safehold
    - Thruster
    - Slew
  - Manage system momentum
  - Sun avoidance for mirror and detector platforms
  - Generate sensor & actuator commands
    - Thrusters
    - Reaction Wheels
    - Star Trackers
    - High Gain Antenna Gimbals
    - Instrument Platform Mechanism
    - Instrument Focus
  - Detect and process ACS faults

- Generic (Heritage) Features
  - Math library functions
  - Onboard modeling
    - Solar Ephemeris
    - S/C Ephemeris

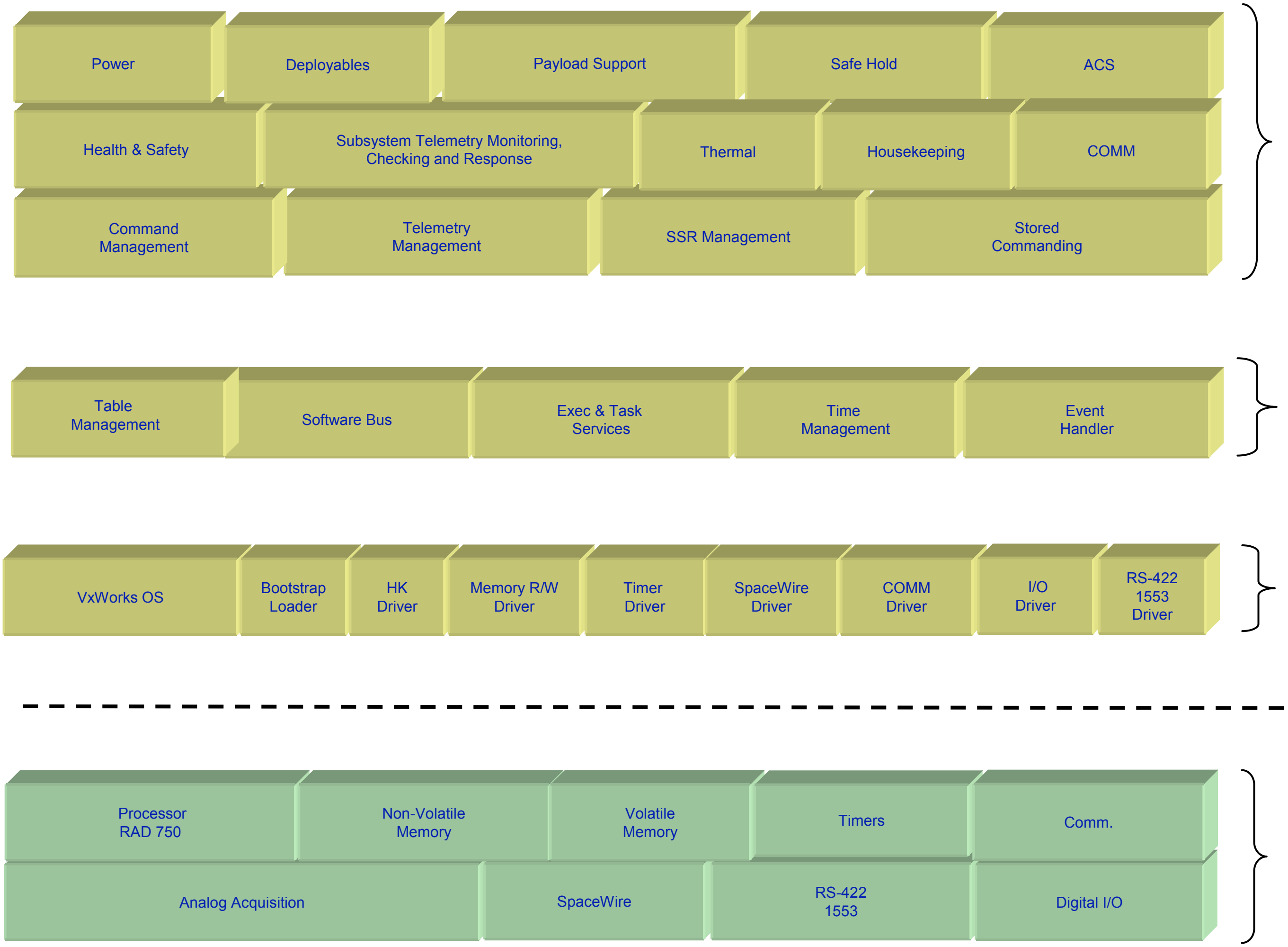
Flight SW Architecture



State Diagram



Processor Layered Software Architecture & Associated Heritage



IXO
Application Layer

- Med/High Heritage For Common Functions (e.g., Stored Commanding, Health & Safety, Command Management),
- Low/No Heritage For Mission Unique Functions (e.g., Deployables, Payload, ACS, power)

System Support Layer
(582's Core Flight Exec)

OS Services Layer
(VxWorks OS,
582 OS Abstraction Layer)

IXO Physical
(Hardware) Layer

Processor Utilization Estimates

					Processor Adjusment		
	25	16	MHz Coldfire (effective rate)	BAE750(%)	12Mhz ST5/SD	115Mhz SDO	60Mhz LRO
	CPU Percentages			Base Value	0.75	7.19	3.75
Component	**50 Mhz**	**32 Mhz**	**Basis of Estimate**				
cFE	0.12	0.19	LRO B2.5 Measured	0.05			0.19
Housekeeping Data Acq	0.12	0.19	LRO B2.5 Measured	0.05			0.19
Health and Safety	0.24	0.38	Estimate	0.10			0.38
Memory Manager	0.01	0.02	LRO B2.5 Measured	0.01			0.02
Memory Dwell	0.17	0.26	LRO B2.5 Measured	0.07			0.26
Stored Commands	0.11	0.17	LRO B2.5 Measured	0.04			0.17
Limit Checker	0.10	0.15	LRO B2.5 Measured	0.04			0.15
Scheduler	1.46	2.29	LRO B2.5 Measured	0.61			2.29
1553 Bus Control	6.96	10.88	LRO B2.5 Measured	2.90			10.88
Command Ingest	0.01	0.02	LRO B2.5 Measured	0.01			0.02
R/T Telemetry Output	2.28	3.56	LRO B2.5 Measured	0.95			3.56
File Manager	0.02	0.04	LRO B2.5 Measured	0.01			0.04
Instrument Manager	16.80	26.25	Estimate	7.00			26.25
Data Storage	2.81	4.39	LRO B2.5 Measured	1.17			4.39
Memory Scrub	1.20	1.88	Estimate	0.50			1.88
Checksum	0.48	0.75	Estimate	0.20			0.75
Thermal Control	0.24	0.38	Estimate	0.10			0.38
Power Control	0.72	1.13	Estimate	0.30			1.13
Spacewire Bus Control	4.80	7.50	Estimate	2.00			7.50
Data Ingest	2.40	3.75	Estimate	1.00			3.75
HGA Control	2.40	3.75	Estimate	1.00			3.75
Attitude Control	96.00	150.00	Estimate	10.00			150.00
ACS Models	9.60	15.00	Estimate	1.00			15.00
Subtotal	**149.05**	**232.89**		**29.10**			

Estimated Resource Margins

For this chart, Margin = (Available – Estimate) / Available

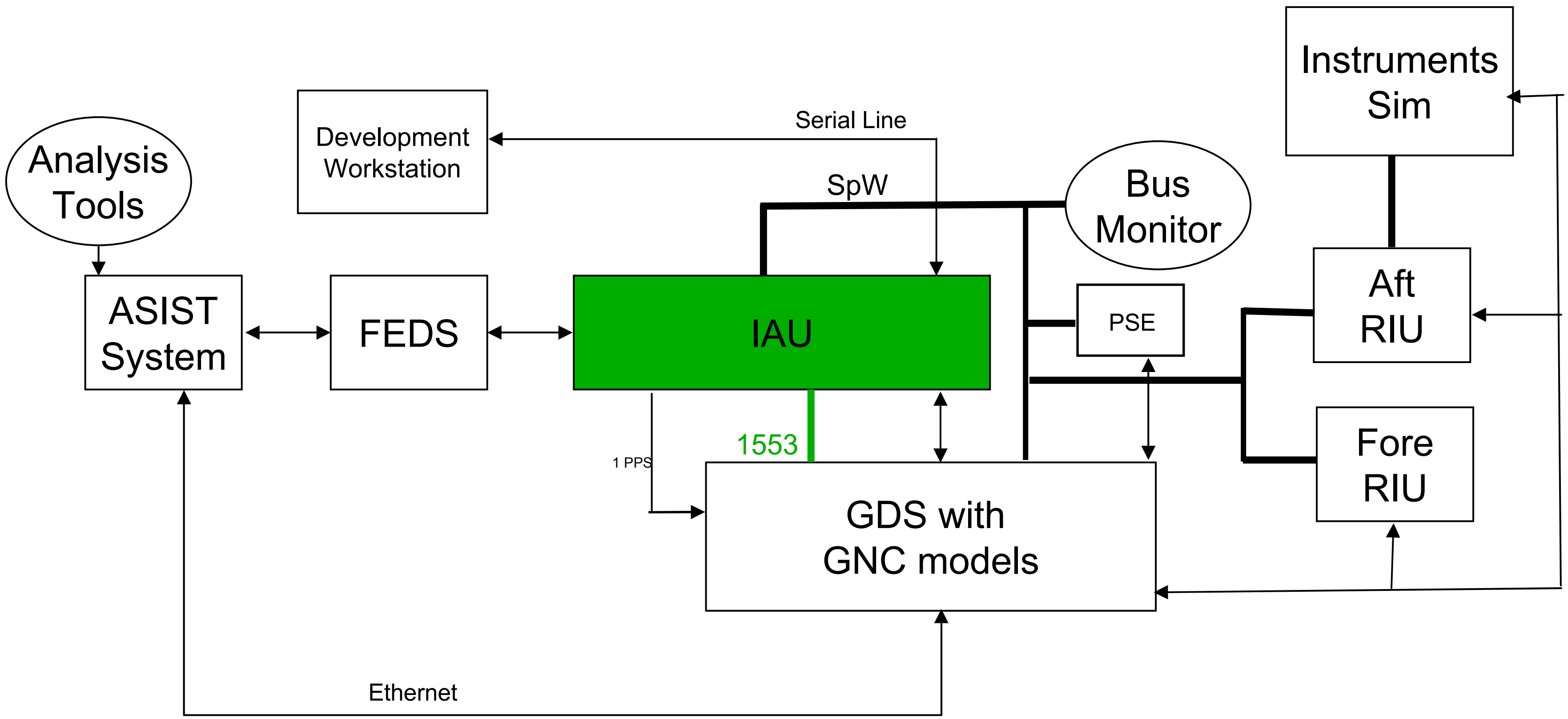
Resource	Amount Available	Current Estimate	Current Margin	GOLD Rule Required Margin @Phase A
CPU (BAE750)	100%	29.10%	71%	50%
EEPROM(kB)	4096	1019	75%	50%
uP RAM(kB)	32768	6471	80%	50%

Code and Memory Estimates

Component	SLOC	EEPROM (KB)	SRAM (KB)		BOE
OS (VxWorks)		410.2	2034		LRO (compressed)
cFE		220.1	3061		LRO
Housekeeping	7214	14.0	40.8		LRO
Memory Manager	3660	6.5	29.8		LRO
Memory Dwell	1187	4.3	24.9		LRO
Stored Commands	8480	40.3	163.4		LRO
Limit Checker	15235	34.6	33.3		LRO
Scheduler	7649	20.7	29.2		LRO
1553 Bus Control	11910	21.9	86.6		LRO
Command Ingest	5306	7.8	31.7		LRO
Telemetry Output	11853	35.6	57.5		LRO
Data Storage	7338	11.5	54.9		LRO
Memory Scrub	7760	20.6	43		LRO
Checksum	7630	20.6	44		LRO
File Manager	7517	13.3	66.3		LRO
Instrument Manager	25000	35.0	350		Estimate
C&DH Library	11863	6.5	9		LRO
Power Control	2000	5.0	20		Estimate
Thermal Control	2000	5.0	20		Estimate
HGA Control	5000	8.0	30		Estimate
Models	6000	10.0	40		Estimate
Attitude Control	30000	40.0	150		Estimate
Data Ingest	2000	5.0	20		Estimate
Spacewire	1000	4.0	10		Estimate
Math Library	7721	4.7	7.8		LRO
GNC Shared Library	7261	6.0	1.6		LRO
Framework	8915	8.1	11.9		LRO
Total	**211499**	**1019.3**	**6471**		

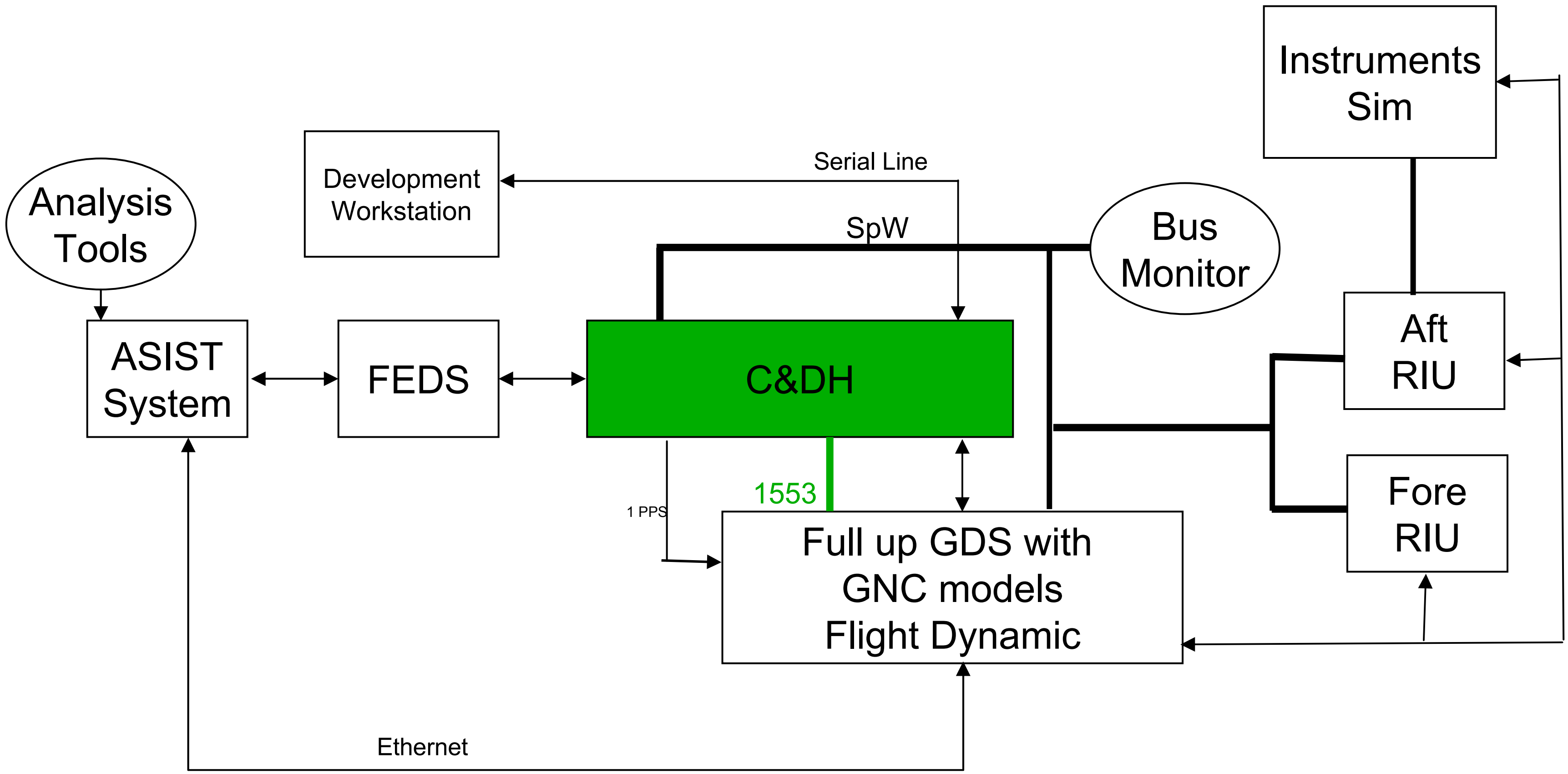
Note: The VxWorks kernel and tasks are compressed in EEPROM. cFE and tables are uncompressed

C&DH / PSE / Thermal FSW Testbed



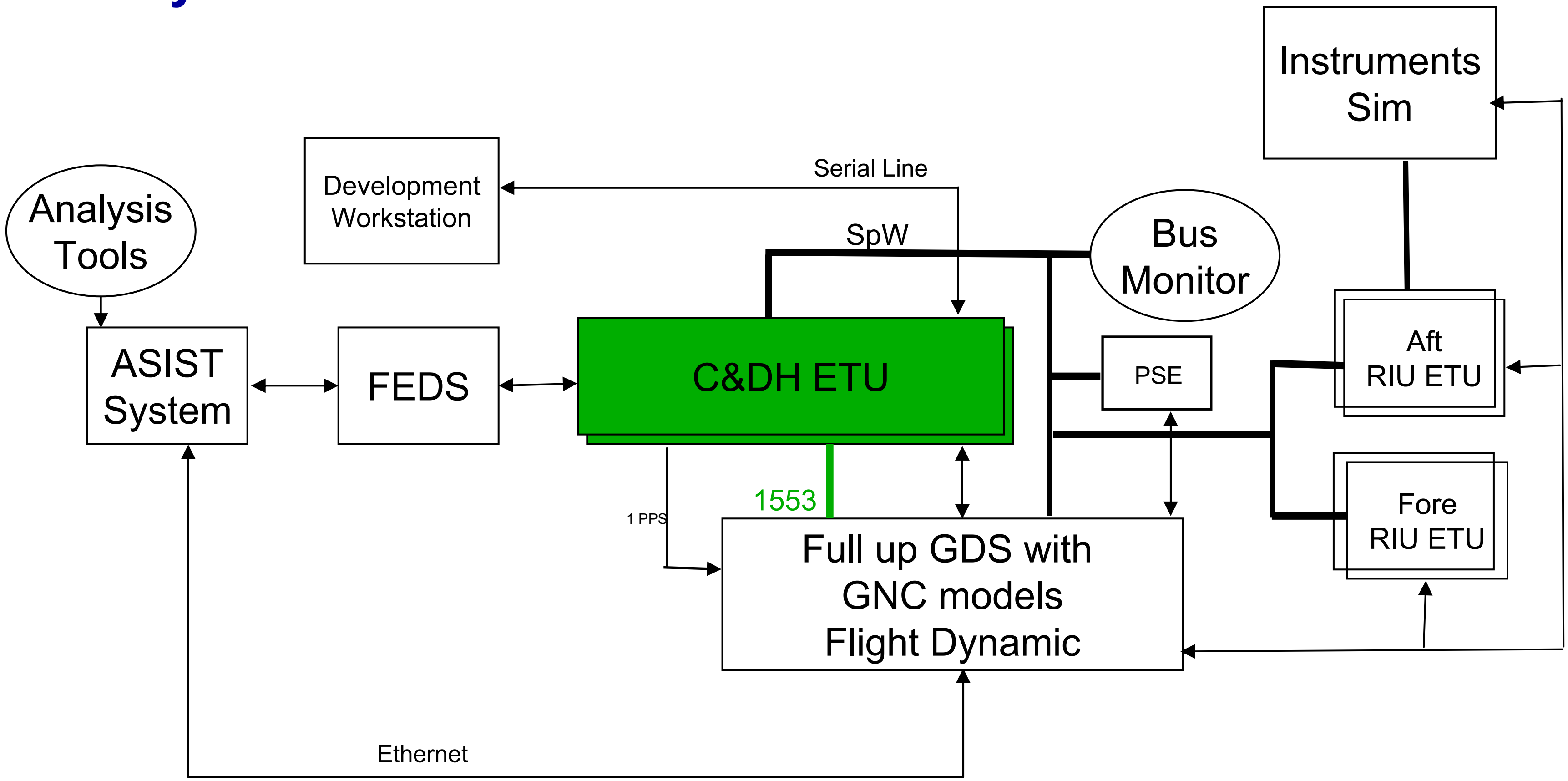
- **Top-Level Requirements:**
  - **Support C&DH FSW development**
  - **Support C&DH FSW build integration**
  - **Support C&DH FSW build test**
  - **GDS to checkout GNC I/Fs**

ACS FSW Testbed



- **Top-Level Requirements:**
  - **Support GNC FSW development**
  - **Support GNC FSW build integration**
  - **Support GNC FSW build test**

FSW System / Maintenance Testbed



- **Top-Level Requirements:**
  - **Support FSW system test**
  - **Support mission operation training**
  - **Support FSW maintenance**

Elements Required For FSW Development (Inc. Deliverables/Receivables)

PROVIDER	ITEM
Flight Software/Code 582	▪ S/C Raw Data Simulator (3) ▪ S/C Simulator (7) ▪ Flight Software Builds
Ground System/Code 583	▪ ASIST GSE (3) ▪ Front-End Simulator (3)
C&DH/Code 561	▪ IAU/Aft & Fore RIU Set (2) ▪ IAU/Aft & Fore RIU ETU set (1)
ACS/Code 596	▪ ACS Dynamic Simulator (3)
Instrument Developers	▪ Instruments Simulator (3)
PSE Developers	▪ PSE BB (1) ▪ PSE ETU (2)

FSW Development Approach

- Reuse LRO C&DH FSW (Med to high heritage, low risk - LRO scheduled to launch 2009)
  - LRO FSW Features (based on 582's Core Flight Executive)
    - Being developed using FSW best practices consistent w/NPR 7150.2
    - Onboard file systems and associated file transfer mechanisms
    - Onboard networks with standard interfaces
    - Standard application interfaces (API) for ease of development and rapid prototyping
    - Dynamic application loading, middleware (SB) provide dynamic cmd/tlm registration
    - POSIX APIs and open source Integrated Development Environment
  - Benefits
    - Will enable parallel collaborative development and system interoperability
    - Will automate many previously manual development activities
    - Will simplify technology infusion and system evolution during development and on-orbit
    - Will enable <u>rapid deployment of low cost, high quality mission software</u>

- New development for all mission specific components
  - ACS, Instrument support, mission-specific ops concept support, power electronics, etc.

Management Approach

- Product Development Process Will Comply with GOLD rules and NPR 7150.2 (NASA Software Engineering Requirements)

- Development
  - Product Development Plan per 582 branch standards, approve by Branch & Project
  - Detailed FSW development schedule integrated with project & subsystems schedules
  - Requirements management using MKS tool
  - Monthly PSR with AETD & project; branch status reviews
  - Weekly system engineering meetings, FSW team meetings
  - FSW Design & Code reviews
  - Major milestones (SCR, PDR, CDR, etc.)

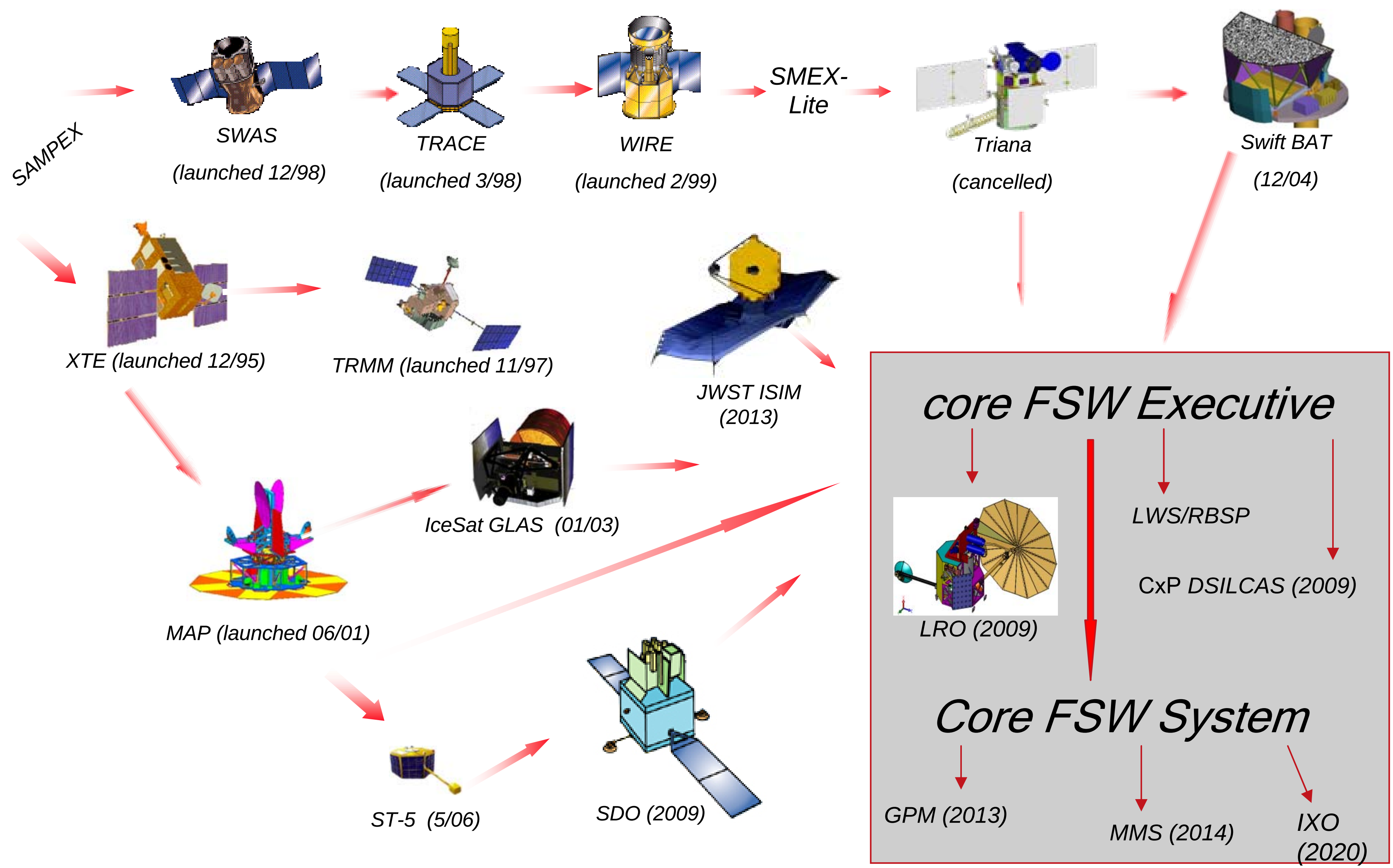
- Configuration Management
  - FSW CM Plan per 582 branch standards, approve by Branch & Project
  - Commercial CM tool (i.e., MKS) to manage source codes and document
  - Proposed FSW changes affecting missions requirements, cost and/or schedule will be forwarded to Project level CCB

- Test Plan
  - FSW Test Plan per 582 branch standards, approve by Branch & Project

Flight Software Maintenance

- Code 582 will provide FSW Maintenance for IXO
- Dedicated FSW Maintenance Team will be responsible for maintaining the FSW
- Maintenance staff will be a part of the FSW Acceptance Test Team
- FSW Maintenance development will be performed in the System/FSW Maintenance Test Bed

GSFC Flight Software Architecture Heritage



Environments

Radiation

Micrometeorite

Solar Cycle Effects

- At Solar Maximum
  - Trapped Proton Levels Lower
  - GCR Levels Lower
  - Solar Events More Frequent & Greater Intensity

- At Solar Minimum
  - Trapped Protons Higher
  - GCR Levels Higher
  - Solar Events Are Less Frequent & Have Lower Intensity

- Solar Min: Calendar years 2016 – 2019
- Solar Max: Calendar years 2020 – 2025
- Solar Min: Calendar years 2026 – 2029

Total Ionization Dose – 10-year Mission

Total mission dose (rad)

Al absorber thickness (mm)	(mils)	($g\ cm^{-2}$)	Total	Solar protons
0.050	1.968	0.014	8.706E+05	8.706E+05
0.100	3.937	0.027	4.634E+05	4.634E+05
0.200	7.874	0.054	2.584E+05	2.584E+05
0.300	11.811	0.081	1.897E+05	1.897E+05
0.400	15.748	0.108	1.501E+05	1.501E+05
0.500	19.685	0.135	1.236E+05	1.236E+05
0.600	23.622	0.162	1.047E+05	1.047E+05
0.800	31.496	0.216	8.077E+04	8.077E+04
1.000	39.370	0.270	6.612E+04	6.612E+04
1.500	59.055	0.405	4.537E+04	4.537E+04
2.000	78.740	0.540	3.406E+04	3.406E+04
2.500	98.425	0.675	2.691E+04	2.691E+04
3.000	118.110	0.810	2.189E+04	2.189E+04
4.000	157.480	1.080	1.574E+04	1.574E+04
5.000	196.850	1.350	1.201E+04	1.201E+04
6.000	236.220	1.620	9.727E+03	9.727E+03
7.000	275.590	1.890	8.007E+03	8.007E+03
8.000	314.960	2.160	6.759E+03	6.759E+03
9.000	354.330	2.430	5.859E+03	5.859E+03
10.000	393.700	2.700	5.075E+03	5.075E+03
12.000	472.440	3.240	4.005E+03	4.005E+03
14.000	551.180	3.780	3.211E+03	3.211E+03
16.000	629.920	4.320	2.651E+03	2.651E+03
18.000	708.660	4.860	2.247E+03	2.247E+03
20.000	787.400	5.400	1.898E+03	1.898E+03

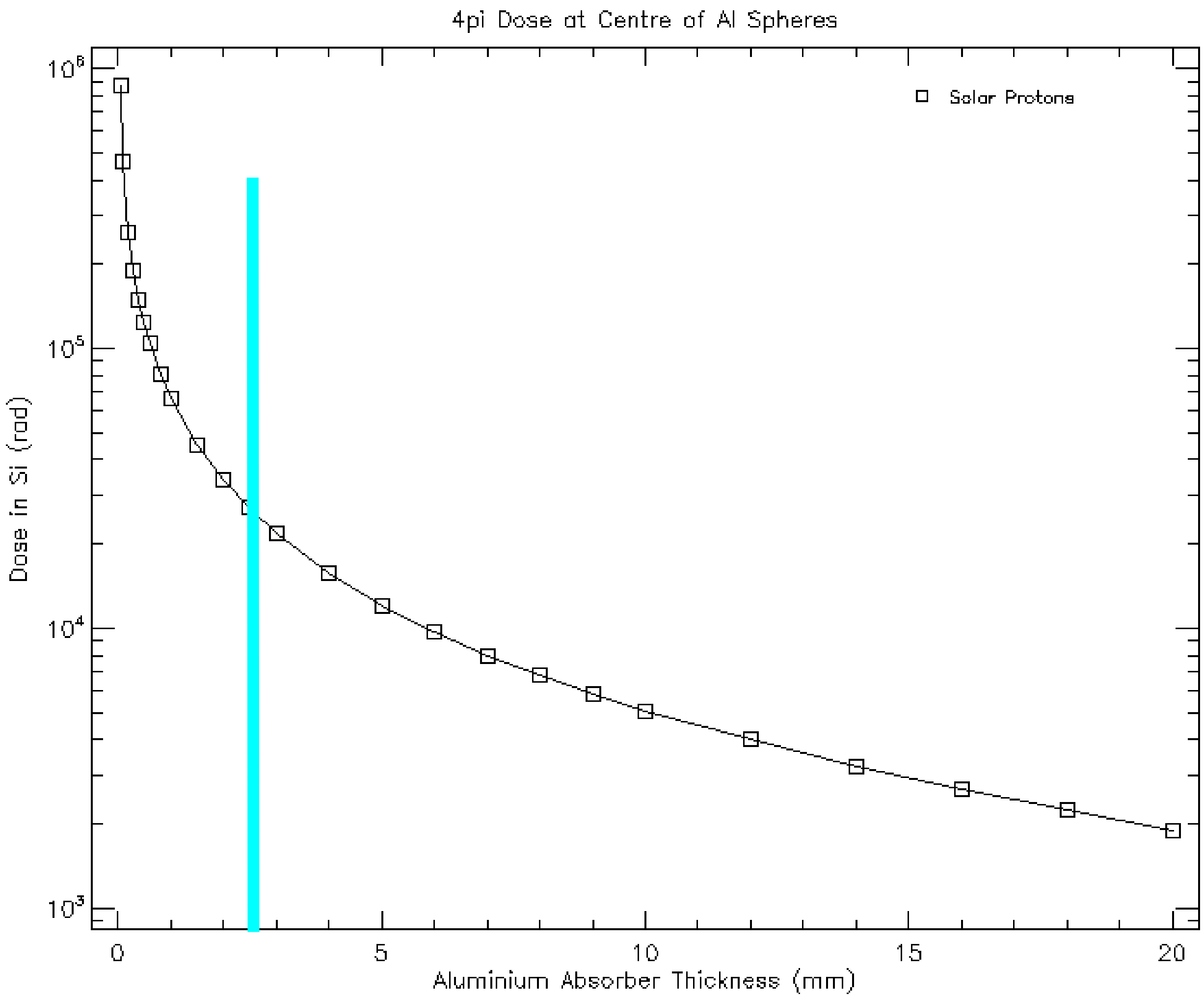
Dose on Si

Values do not include 2x standard design margin

< Standard level for 100-mil Al equivalent shielding:

- 27 krad

10-year Extended Mission Dose-Depth Curve



Values do not include 2x standard design margin

Radiation Environment for 2020 Launch

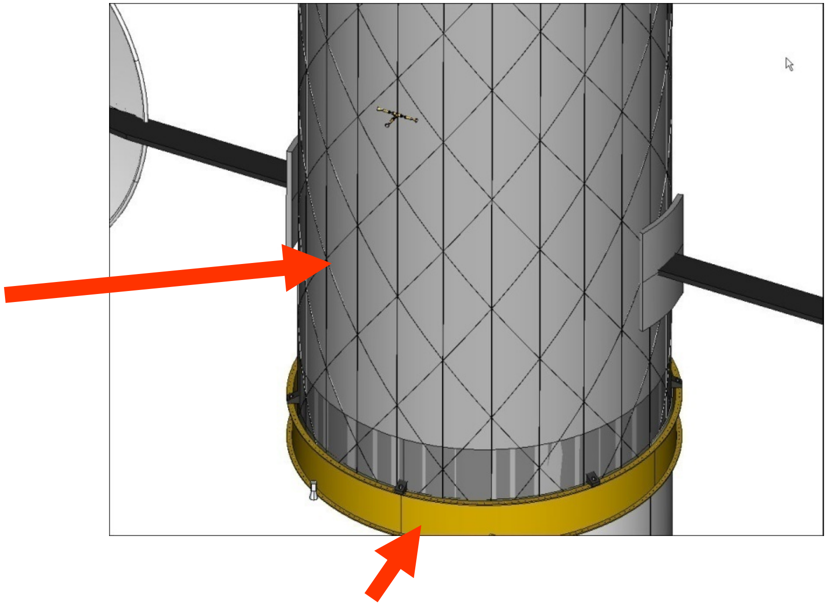
- Earth-L2 TID ~ 100 rad @ 100 mil Al shielding:
  - Insignificant in total TID
- 5-yr design mission: 23 krad on Si @ 100 mil Al shielding:
  - Design for 46 krad
- 10-yr extended mission:
  - 27 krad on Si @ 100 mil Al shielding (due to solar min. conditions).
  - Design for ~ 54 krad

- Severe Environment for Single Events Effects
  - Devices fully exposed to Galactic Cosmic Rays and heavy solar particles
  - See background slides for a template SEE mitigation plan
  - Mitigation techniques are required for SEE vulnerable parts
    - Triple modular redundancy (TMR) works well for FPGAs
    - Error detection hardware is needed for masking out bit flips, resets, cycling power, etc.

Contamination Control

- Particulate and molecular contamination-control requirements for the X-ray optics
  - On the order of 10 micrograms per cm2 at EOM, looser than the values required by and achieved for Chandra.
- Particulate and molecular contamination-control requirements for the instruments
  - > 10 micrograms per cm2 at EOM (somewhat looser than on the optics)
- Purge until T-0 is required on the FMA and some instruments

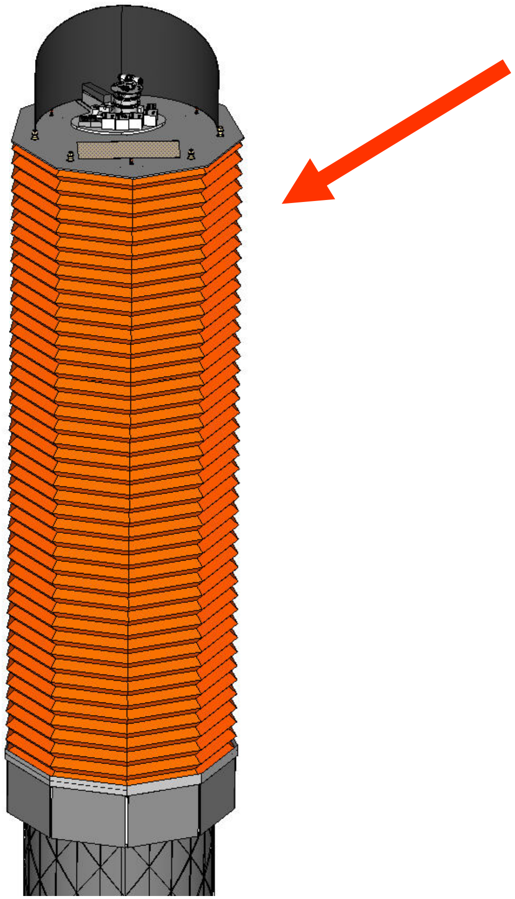
Micrometeorite Threat - Fixed Metering Structure and FMA



- **Fixed Metering Structure:**
  - About 1-2 micrometeoroid penetrating impacts expected.
  - Estimated minimum impactor diameter is 0.091 cm.
  - Low probability of impactors of more than 0.3 cm diameter.
- **Flight Mirror Assembly:**
  - For the purpose of this study, failure is defined as penetration of the assembly. The geometry of the Flight Mirror Assembly (FMA), as well as the arrangements of the mirror foils, limits the probability of micrometeoroid penetration from this side of the observatory. The working assumption is that micrometeoroids striking the FMA are crushed when impacting multiple internal surfaces, while the separation from the FMA to the bus and the instrument module and the internal baffles allows for energy to dissipate, further reducing the threat of micrometeoroids coming from the FMA side.
  - More detailed studies should be conducted to assess the probability of damage to the FMA due to micrometeoroids.

Results are conservative

Micrometeorite Threat - Shroud

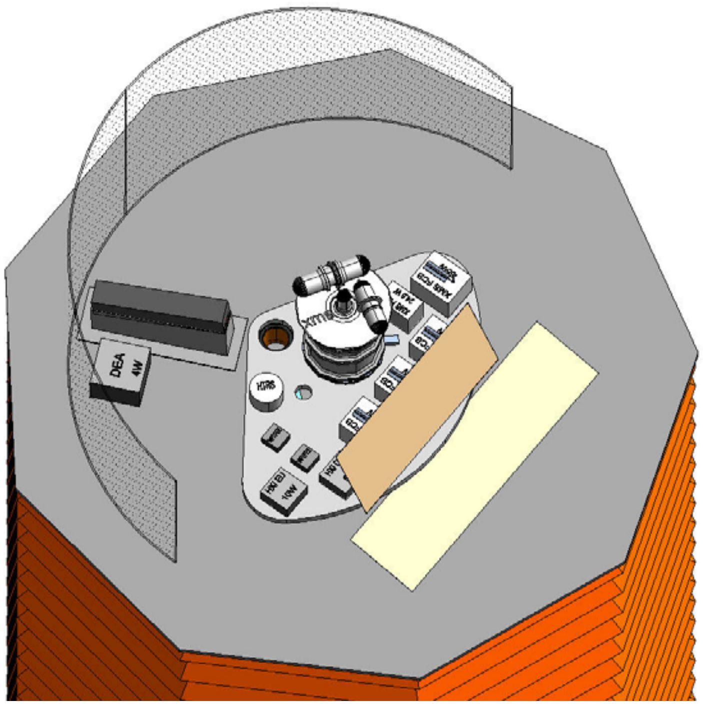


- **Shroud:**
  - **Redesigned shroud, with two MLI blankets separated 10 cm (producing the effect of a Whipple shield), provides protection against micrometeoroids.**
  - **Low-level assessment for MLI blankets predicted a large number of penetrations, due to limitations of the available methods.**
    - **Hypervelocity Impact engineers have more advanced models, allowing less conservative and more accurate results.**
    - **About 35 penetrations of the MLI shroud, with a minimum impactor diameter of 0.04 cm (information provided by Eric Christiansen, Hypervelocity Impacts expert at JSC).**
  - **Failure is defined as penetration of the innermost MLI layer.**
  - **Hole diameter not uniform; the outermost MLI layer is the smallest.**

Results are conservative

Micrometeorite Threat - Instrument Module

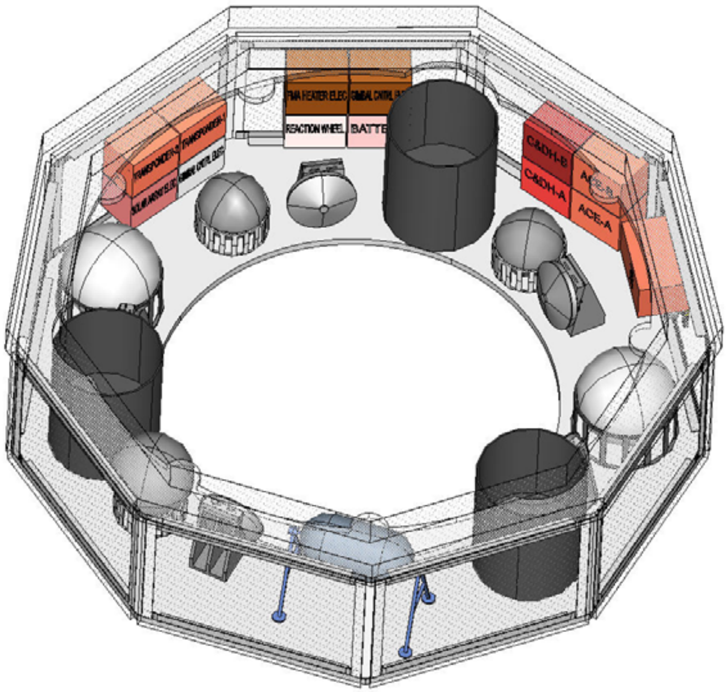
Failure is defined as penetration of the instrument or box housing. It is assumed that no particle crosses the FMA and reaches the Fixed Instrument Platform from the inside.



Instrument	Probability of penetration	Minimum particle diameter (cm)
XMS	0.13%	Ø 0.126
XGS CCD	1.80%	Ø 0.057
WFI/HXI	0.81%	Ø 0.057
HTRS	1.11%	Ø 0.057
XPOL	0.91%	Ø 0.057
Exposed Electronic Boxes	0.83%	Ø 0.057

Results are conservative

Micrometeorite Threat - Central Bus Area



- **Hydrazine Tank:**
  - **Largest tank used as representative of all the tanks.**
  - **Low probability of damage (0.14%) by particles Ø 0.154 cm or larger.**
- **Electronic Boxes:**
  - **0.01% probability of penetration. This is representative of all the electronic boxes on that section.**

Results are conservative

Micrometeorite Threat - Summary

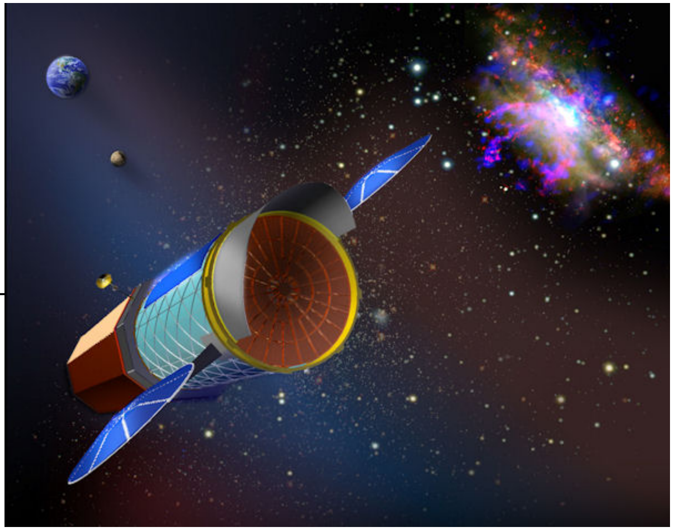
- Current IXO design is compliant with NASA regulations regarding limiting the generation of space debris.
- Collision with micrometeoroids at L2
  - Although NASA-STD-8719.14 requires such analysis only for missions on Earth or Moon orbit, the assessment was performed to ensure that the micrometeoroid environment at L2 does not represent a threat to mission success
  - The shroud is considered one of the most vulnerable components due to its large area and non-rigid composition (two MLI blankets with a middle gap, producing a Whipple-shield effect). However, only about 35 penetrations are predicted. The critical (minimum) diameter of the penetrating particle is 0.04 cm
  - Since the shroud is not a solid panel, but two layered MLI blankets, a small penetration may be covered by the damaged Kapton layers, reducing or eliminating stray light

CONCLUSION: The micrometeoroid protection for the payload, structures, electronic boxes, and tanks is satisfactory

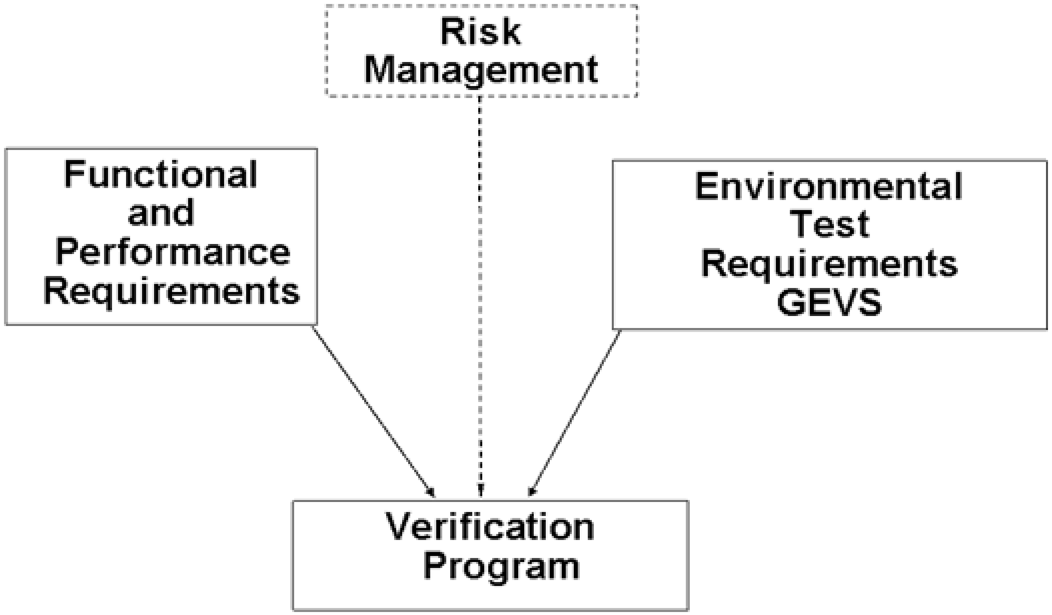
- Results are preliminary. More detailed analyses to be performed.

IXO Systems Definition Document
Chapter 8

Integration and Test



Verification Program Overview



- Establish confidence that the Mission will be a success
- Verify:
  - Functional, Performance, and Operational Requirements
  - Requirements
  - Mission Level Functional, Performance, Interface, and Operational Requirements
  - Workmanship Standards
  - Materials Control
  - Quality Assurance

I&T Purpose and Scope

- Develop and Verify Command and Telemetry Database
  - All Commands and Telemetry Must be Exercised at Least Once
- Maintain a Safe Environment For I&T Personnel and Flight H/W
- Maintain the Cleanliness Conditions for the IXO S/C & Instruments
- Verify all Flight Mechanical and Electrical Interfaces
- Perform Environmental Qualification of the IXO Observatory
- Verify Observatory Performance Requirements are Met Throughout the Environmental Test Program, Including (to the extent possible) Instrument Performance in Thermal Vacuum
- Verify Observatory Compatibility with IXO Mission Operations Systems
- Make IXO Ready For Launch, assist in integration to launch vehicle.

I&T Assumptions

- At each assembly level, the hardware structures to be assembled are delivered fully qualified.
- The S/C bus will be integrated with the metering structure to form the spacecraft module.
- The spacecraft module will then be integrated with the deployment module.
- Lastly, the instrument module and the optics module will be added to form the observatory.
- The observatory will be tested fully extended in a thermal-vac chamber, in the vertical position. Testing during thermal-vac should include, if possible, alignment testing using an X-ray source (but no focus testing).
- Optical (or UV) GSE collimated sources will operate with a compatible detector on the Movable Instrument Platform to monitor system level mirror and alignment performance
  - A fifth stop position would position the GSE detector at mirror focus
- The observatory will not undergo vibration testing, due to concerns about overstressing the flight mirror assembly.

Models Philosphy

- In accordance with NPR 8705.4 Risk Classification for NASA Payloads for a Class A mission
- Engineering model hardware for new or significantly modified designs will be used.
- Protoflight hardware (in lieu of separate proto-type and flight models) except where extensive qualification testing is anticipated.
- Spare (or refurbishable prototype) hardware as needed to avoid major program impact

Calibration, Focal Plane Stimulators

- Calibration sources in X-Ray are not compatible with full-up observatory configurations
  - All calibration with X-Ray sources must be in vacuum
  - Collimated calibration sources require long distances
  - Collimated large aperture calibration sources require large facilities
- Full X-ray and optical characterization of the FMA is done prior to Observatory I&T
  - During Observatory I&T, alternate optical sources will be used to monitor optical stability
- Instrument Calibration performed prior to deliver to I&T
  - In some cases, instruments may need to be calibrated with the flight FMA
- At Observatory I&T, a combination of sources will be used to monitor end to end performance
  - Optical (visible, UV) Sources
    - Collimated, useful for measure of focus to visible/UV GSE detector on MIP
    - Used in vacuum and ambient conditions
  - X-ray Sources
    - Uncollimated, most useful for throughput measurements with flight instruments
    - Only used in vacuum
    - Electron gun with metal target – Manson Source
    - Radioactive sources
    - Detected by flight science instruments
  - The TADS and external optical metrology
    - Linked to FMA and instrument relative alignment
    - Ambient and vacuum

SM Integration – Propulsion Considerations

- The IXO propulsion system is not modular (no separate propulsion module)
  - IXO propulsion is highly integrated to the S/C Bus and Isogrid, with many propulsion interconnections between the two.
    - Propulsion integration should not begin until S/C Bus and metering structure are mated
- Significant time for welding and X-ray inspection are required, which are hazardous to flight electronics and personnel
- Only propulsion mechanical and electrical integration, propulsion thermal, and possibly SM thermal installations can go on in parallel.
- Requires 21 weeks to complete [ref., MDL Propulsion final report]*
  - 5 days per week
  - Welding during regular hours, inspection on off-shift
  - Must be ‘up front’, before avionics are installed

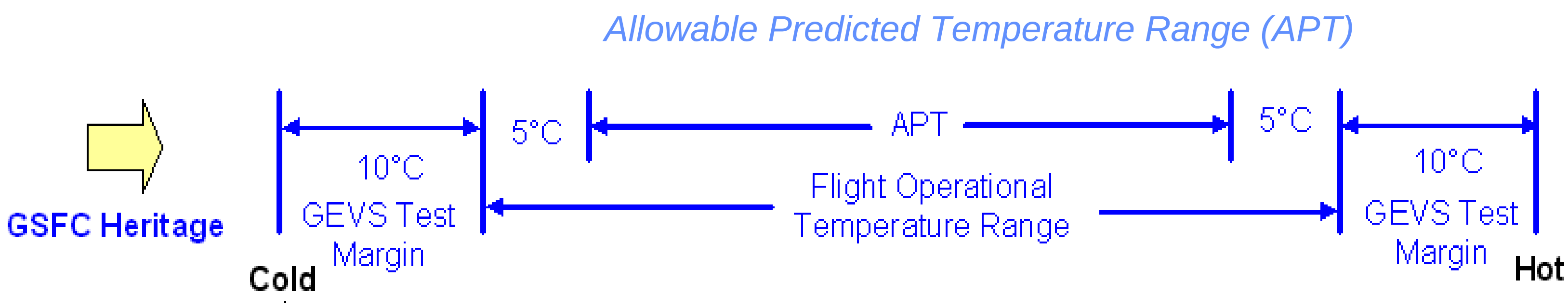
Observatory Thermal Verification Strategies

- Perform Thermal Vacuum Thermal Balance Testing Per GEVS at System level.
  - Perform 4 Hot/Cold Thermal Vacuum Cycles
  - Perform Thermal Balance Tests Subjecting IXO to Worst
  - Hot and Cold Case Conditions.
  - Verify IXO Thermal Models, Perform Model Correlation to Test Data.
  - Verify Proper Operation and Design of Heater Circuits
  - Verify Proper Thermistor Calibration, Operation and Placement
  - Verify Instrument Payload to S/C Interface
  - Verify HGAS to S/C Interface
  - Verify S/A to S/C Interface

Verification Matrix – sample, for all Subsystems

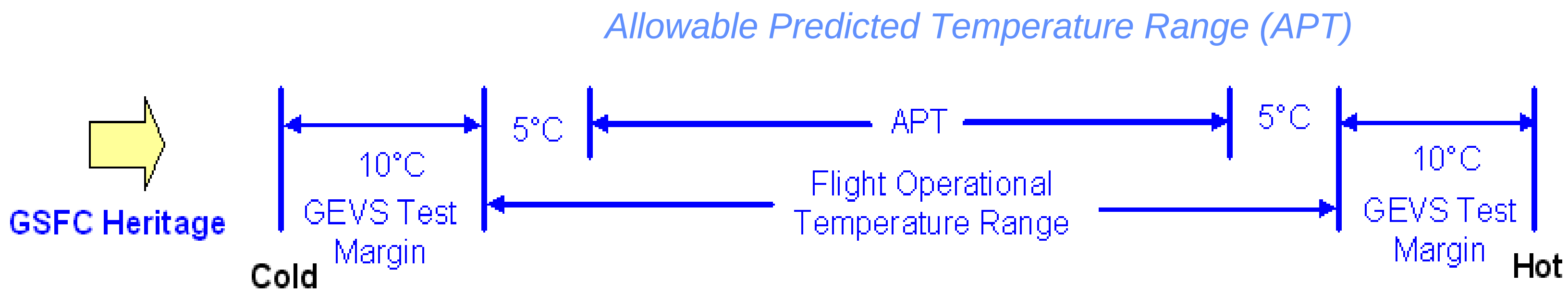
I&T Phase	Verif. Desc. (Requirement)	Assy Level	Model	Verif. Method	Level	Facility	GSE	Simulators	Comments
…	…	…	…	…	…	…	…	…	
Pre-Delivery	Structural / Vibration	Full up Structure w/o other items	PFU	T	Qual	GSFC B7	Mass Simulators for all Flight Hware items	none	
…	…	…	…	…	…	…	…	…	
I&T 1.d	Propulsion Plumbing Pressure Test	Metering Module	PFU	T	Qual	TBD	Pressure Test Hware	none	
…	…	…	…	…	…	…	…	…	
I&T 3.b	Vignetting Test	Observatory Full Min. Config.	PFU	T	Accept.	TBD	Pencil Xray Source, Alignment Fixture	TBD	

Instrument Module Temperature Margin Definition (During IXO Instrument TV Test)



- *APT is defined within at least 5°C of flight operational temperature range which is consistent with GSFC heritage. <u>Thermal math model (TMM) predictions will be compared to APT</u>.*
- *Spacecraft test margin is defined as 10°C above flight operational temperature range which is observatory level TV qualification soaks. Instruments with correlated TMM can test 10°C outside of APT.*

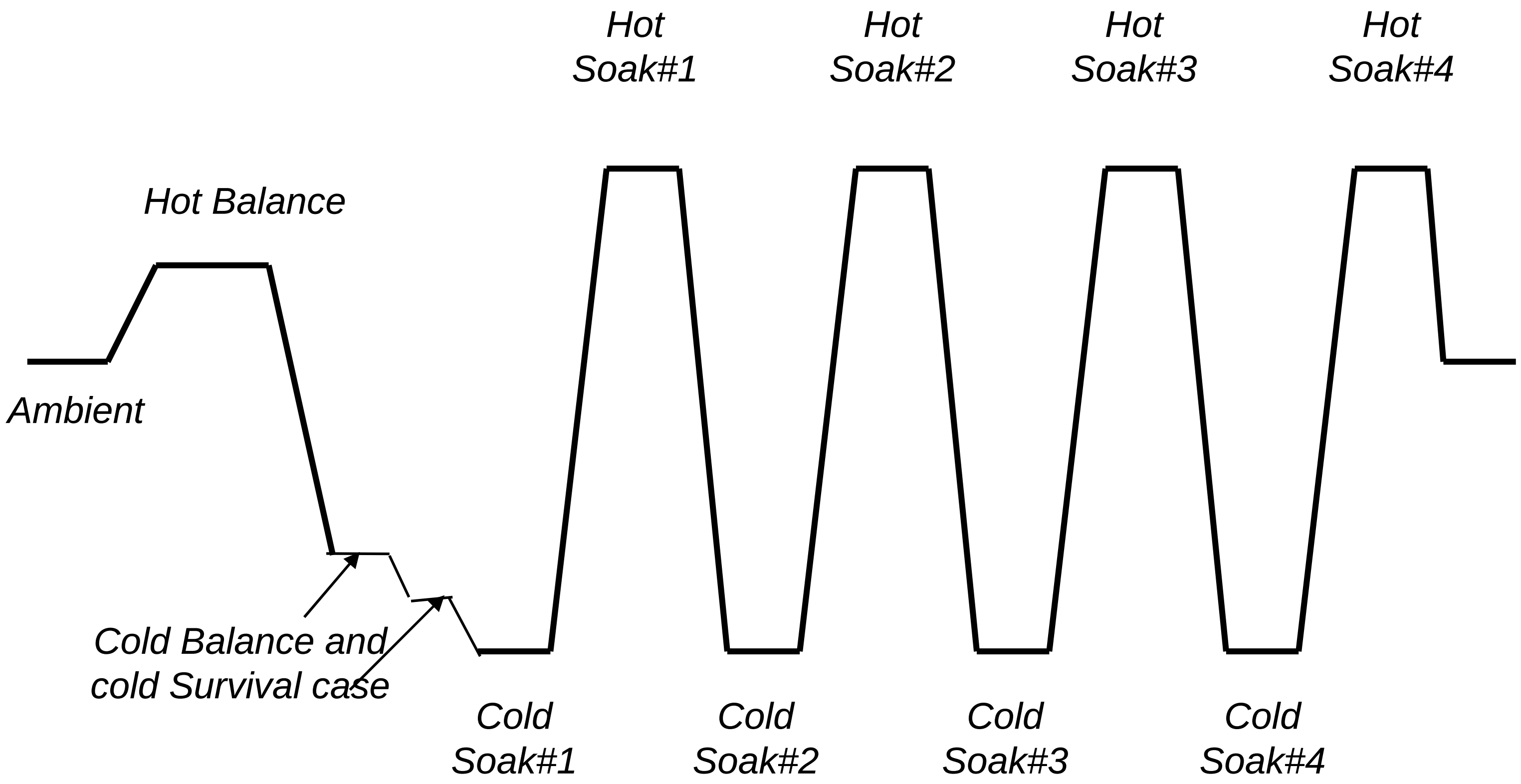
Spacecraft Bus, Fixed Metering Structure, and FMA Temperature Margin Definition (During IXO Observatory TV Test)



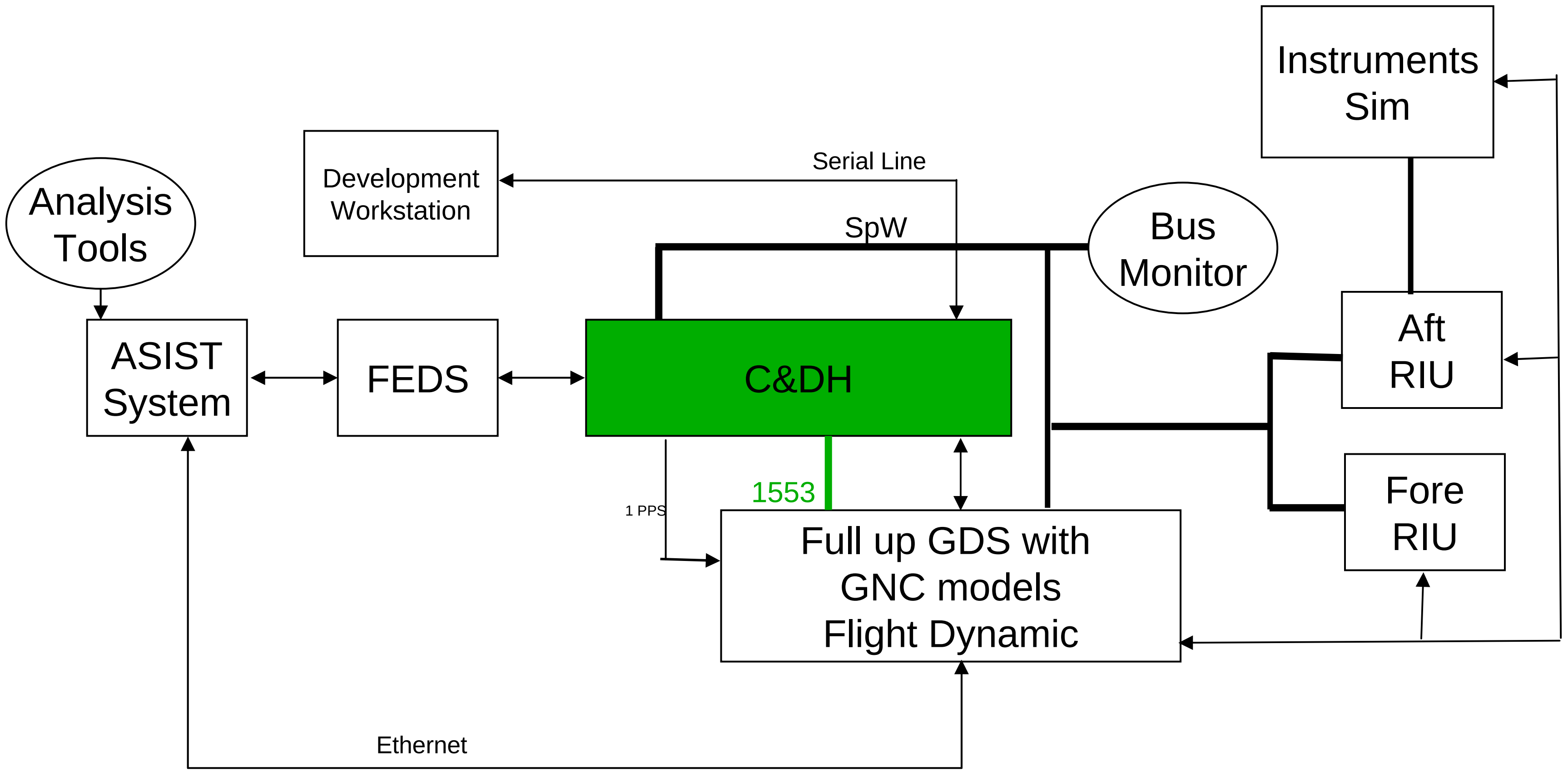
•APT is defined within at least 5°C of flight operational temperature range which is consistent with GSFC heritage. <u>Thermal math model (TMM) predictions will be compared to APT</u>.

•Spacecraft test margin is defined as 10°C above flight operational temperature range which is observatory level TV qualification soaks. Instruments with correlated TMM can test 10°C outside of APT.

Observatory TB/TV Test Profile at System Level

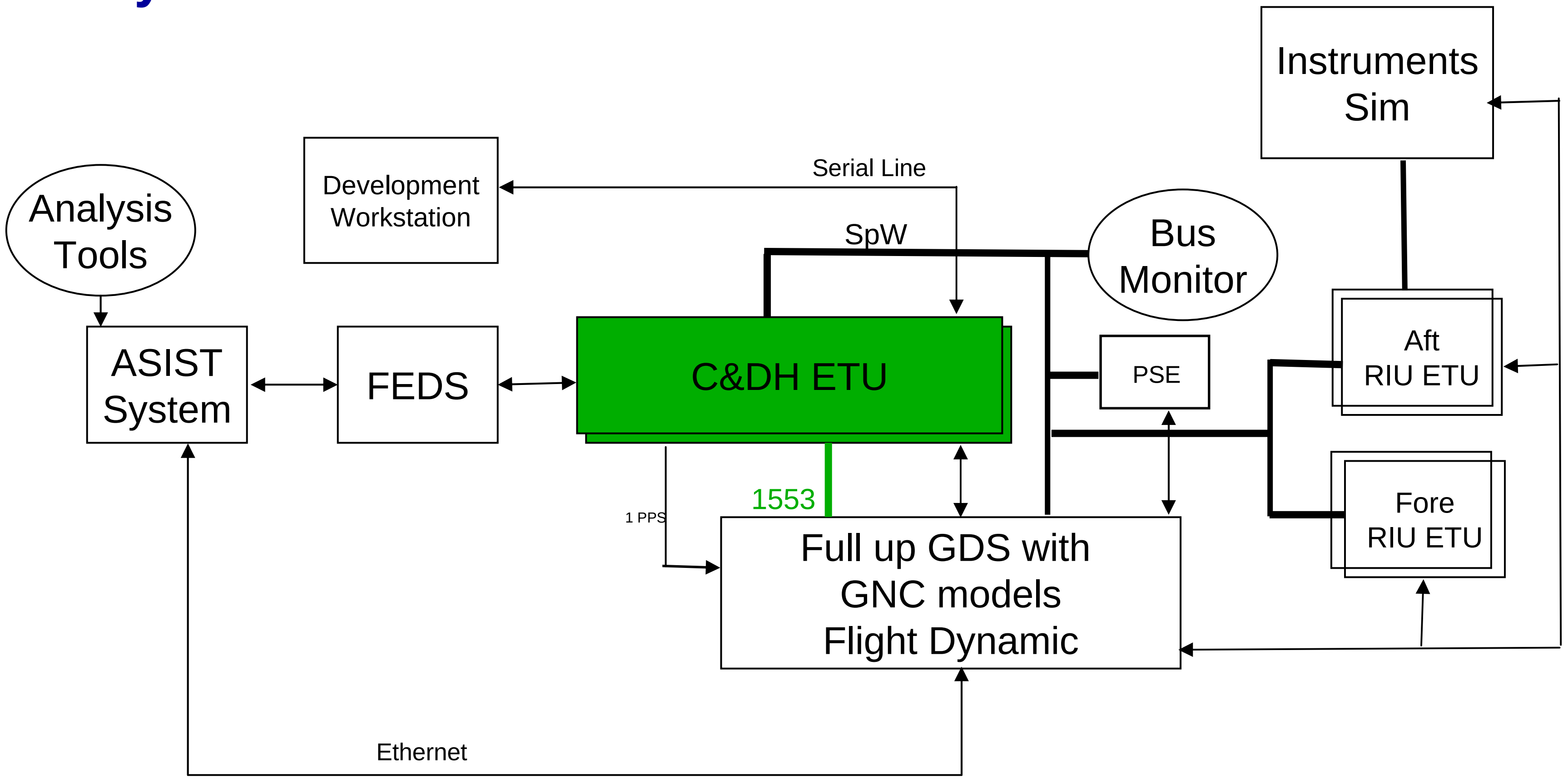


ACS FSW Testbed



- **Top-Level Requirements:**
  - **Support GNC FSW development**
  - **Support GNC FSW build integration**
  - **Support GNC FSW build test**

FSW System / Maintenance Testbed



- **Top-Level Requirements:**
  - **Support FSW system test**
  - **Support mission operation training**
  - **Support FSW maintenance**

FSW Verification and Validation

- Unit Test
  - Done by developers using PC tools
  - Follow Branch 582 Unit Level Test Standard - Tailored
  - Includes Path testing, Input/Output testing, Boundary testing, and Error Reporting verification
  - Occasionally BB H/W is required to verify H/W I/F
- Build Integration Test
  - Done by developers to verify that the FSW performs properly on the BB H/W in the FSW testbeds using embedded system tools
  - First level functionality ensured for integrated software
  - Build Test Team to assist in GSE I/F checkout
- Build Verification Test
  - Done by independent test team with GNC Analyst support on the BB H/W in the FSW testbeds using embedded system tools
  - Test each requirement in the Flight Software Requirements documents (where possible at the build level)
  - Use test scenarios to test requirements in both a positive and negative fashion.
  - Scenarios constructed to combine requirements that are logically connected to create a test flow.
  - Automation to be utilized as much as possible
  - Requirements Traceability Matrix maintained

FSW Verification & Validation (cont)

- System Test
  - Done by independent test team including Flight S/W Maintenance & Flight Operation Team members with support from GNC analyst, IXO system & subsystems
  - Top-down approach with end-to-end testing
  - Test scenarios will focus on the operational aspects of the flight software. For each test, as much as practical, all software will be running, including all C&DH, ACS and PSE applications with checks and responses enabled
  - Stress test of the FSW will demonstrate correct performance at peak CPU and bus loading
  - Perform negative testing from an operational perspective, system level failure modes test & analysis
  - Flight qualify Ground System Telemetry & Command Database
  - Test scenarios can be used to support S/C CPT
  - Tests will be Performed on System/FSW Maintenance Testbed

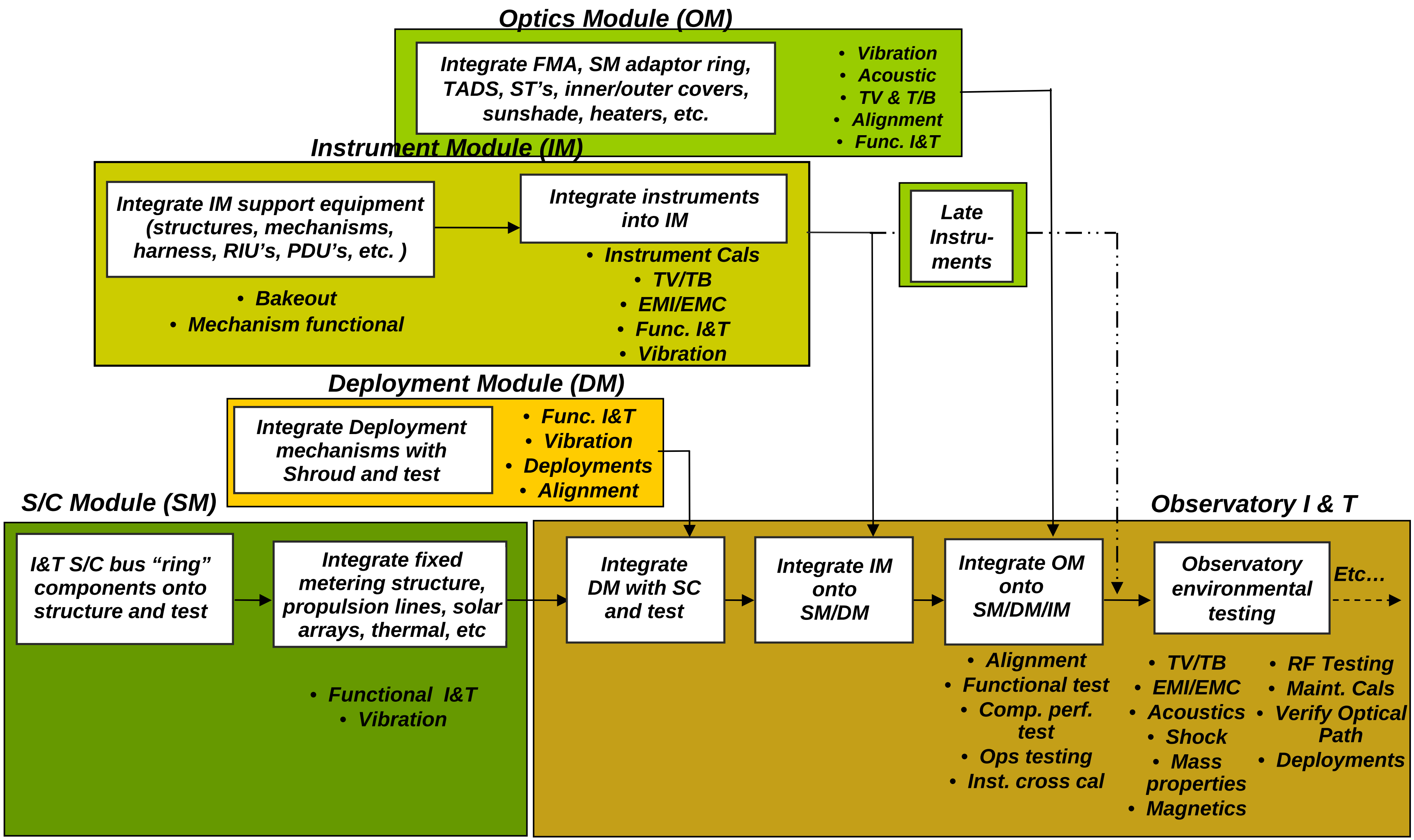
Elements Required For FSW Development (Inc. Deliverables/Receivables)

PROVIDER	ITEM
Flight Software/Code 582	▪ S/C Raw Data Simulator (3) ▪ S/C Simulator (7) ▪ Flight Software Builds
Ground System/Code 583	▪ ASIST GSE (3) ▪ Front-End Simulator (3)
C&DH/Code 561	▪ IAU/Aft & Fore RIU Set (2) ▪ IAU/Aft & Fore RIU ETU set (1)
ACS/Code 596	▪ ACS Dynamic Simulator (3)
Instrument Developers	▪ Instruments Simulator (3)
PSE Developers	▪ PSE BB (1) ▪ PSE ETU (2)

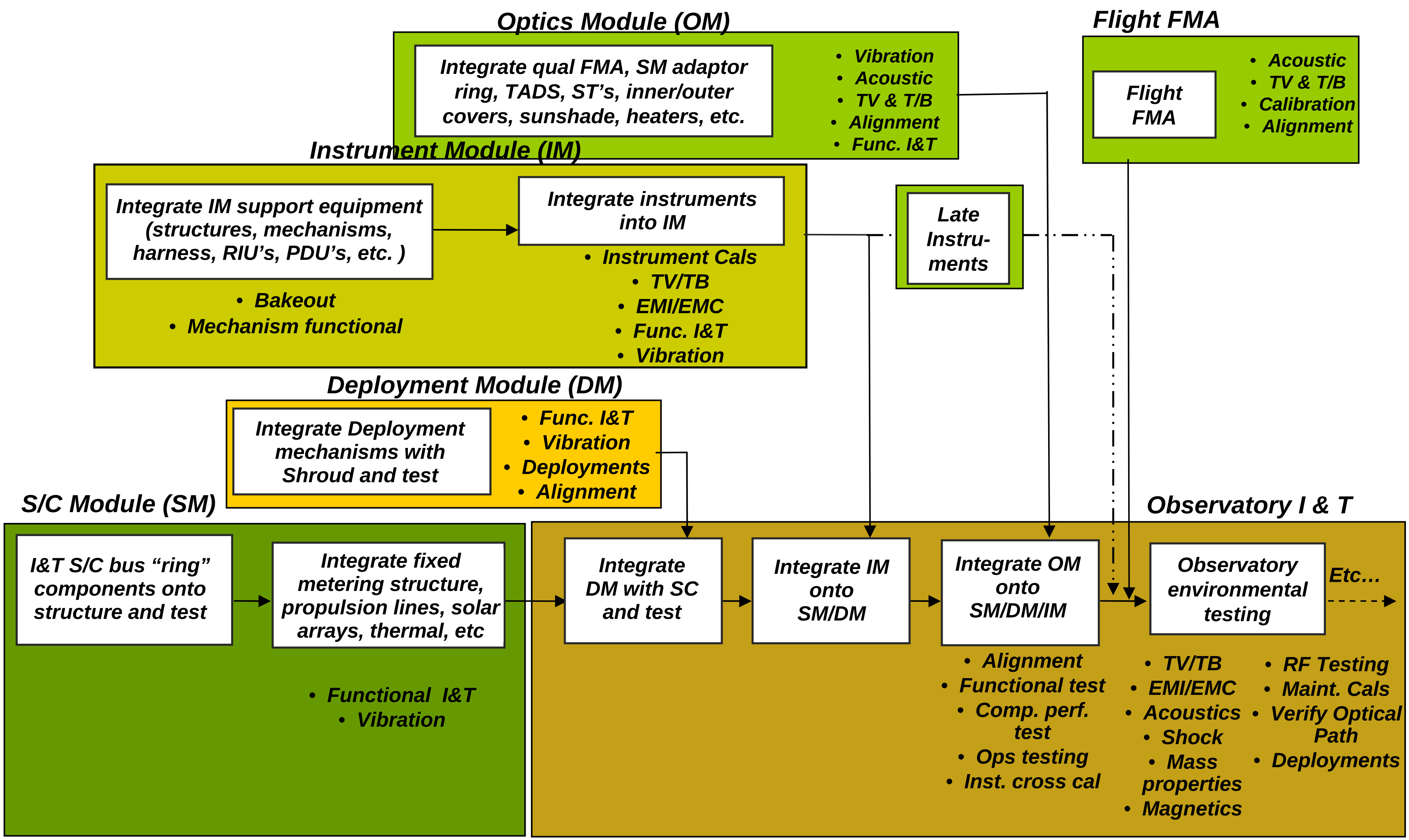
Contamination Control

- Rigorous contamination control including special filtration, constant mirror purge, continuous real time monitoring, scheduled cleanings and black light inspections.
  - Preserves science integrity. Must be considered in selection, configuration and operation of facilities, cost driver, schedule driver.
- X-ray point source GSE used to monitor contamination in optical path, especially FMA.
  - Gives realistic measurement of science degradation, indicate contam event.
- Final S/C environmental testing performed with no mass simulators, mockups, protoflight units etc.
  - Enables Test as you fly, demonstrates self compatibility, more important since end-to-end science testing not possible.
- Structural verification model (2nd flight like structure) built and used for modal surveys, to verify structure models, to practice alignments w/o risking contamination on flight structure.
  - Reduces Risk

IXO High Level I&T Flow – Nominal Plan Overview



IXO High Level I&T Flow – Contingency Plan Overview

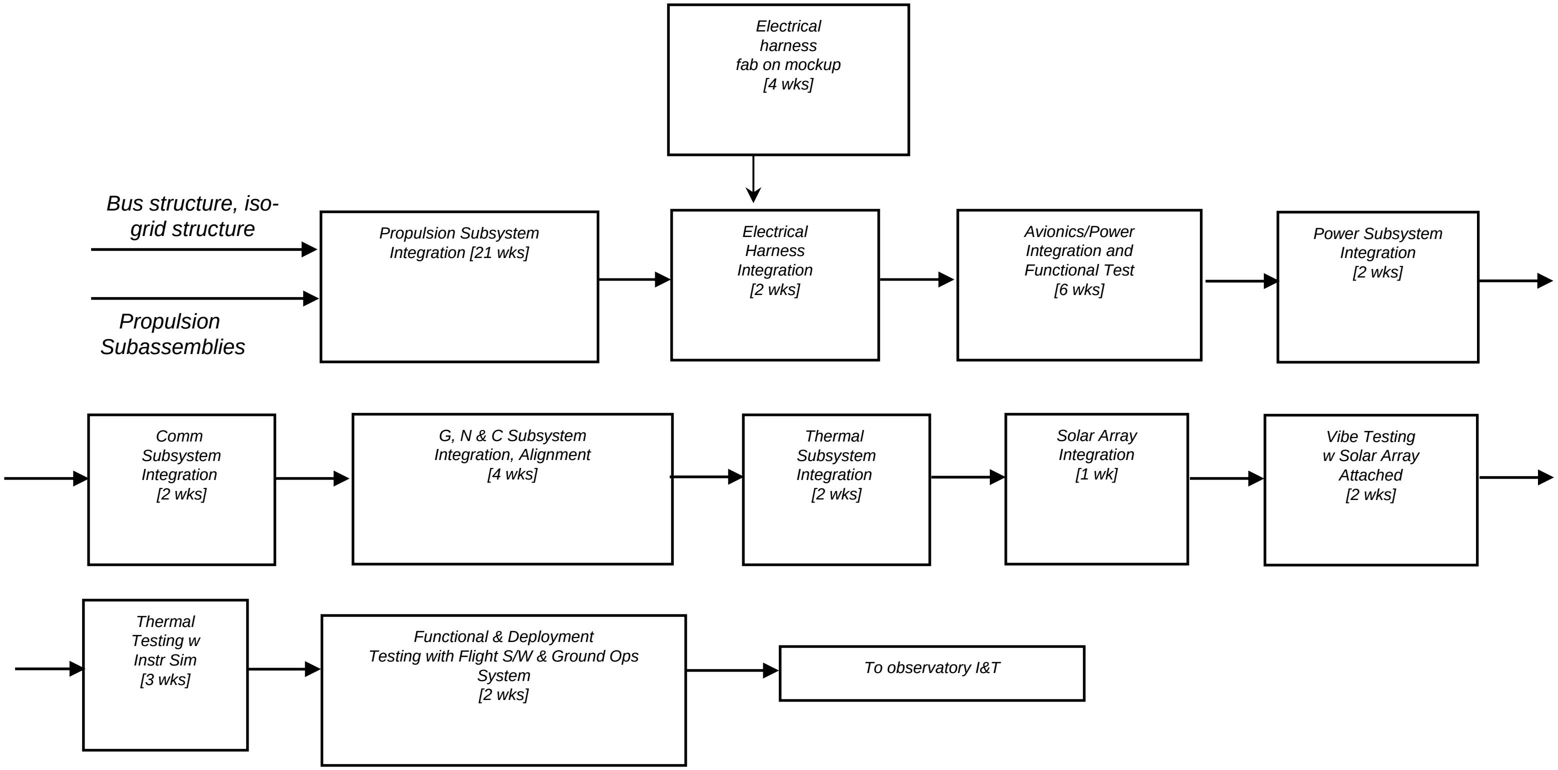


IXO Observatory Test Matrix

Hardware Description			Structural / Mechanical																	Thermal/Vacuum						Electromagnetic					Analysis		
Hardware	Hardware Classification	Quantity	Mass Properties	ICD / Size / Envelope	Modal Survey	Deployed Frequency	Random Vibration	Sine Vibration	Signature Sine Sweep	Loads	Shock	Acoustics	Ambient Deployment	Alignment / Alignment Verification	Max. Exp Operating Pressure	Leak	Flow	Venting	Life (formerly "Life - Vacuum")	Thermal Cycles (not in vacuum)	Bakeout	Thermal Vacuum	Number of Thermal Cycles	Thermal Balance	Thermal Vacuum Deployment	EMI/EMC	Magnetics	Flash / Illumination	RF System	Antenna Pointing	Structural/Thermal/Optical	Stress Analysis	Thermal Analysis
Observatory *All Flight Components*	PF	1	T	I	-	-	-	-	-	-	T	T	T	T	-	T	-	I, An, T	-	-	T	T	4	T	-	T	T	T	T	An	An	An	An

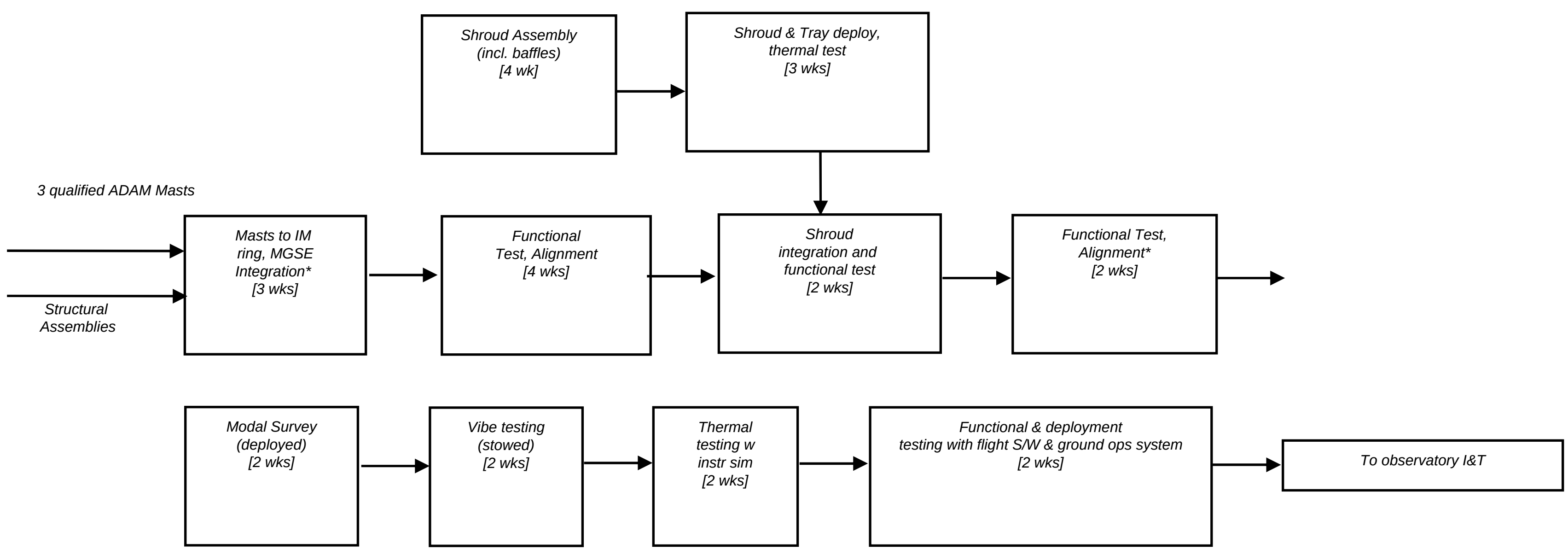
S/C Module Integration & Test – Top-Level Flow

- Assumptions
  - Structure Strength qualified
  - All boxes environmentally qualified
    - EMI/EMC
    - Vibration
    - Thermal



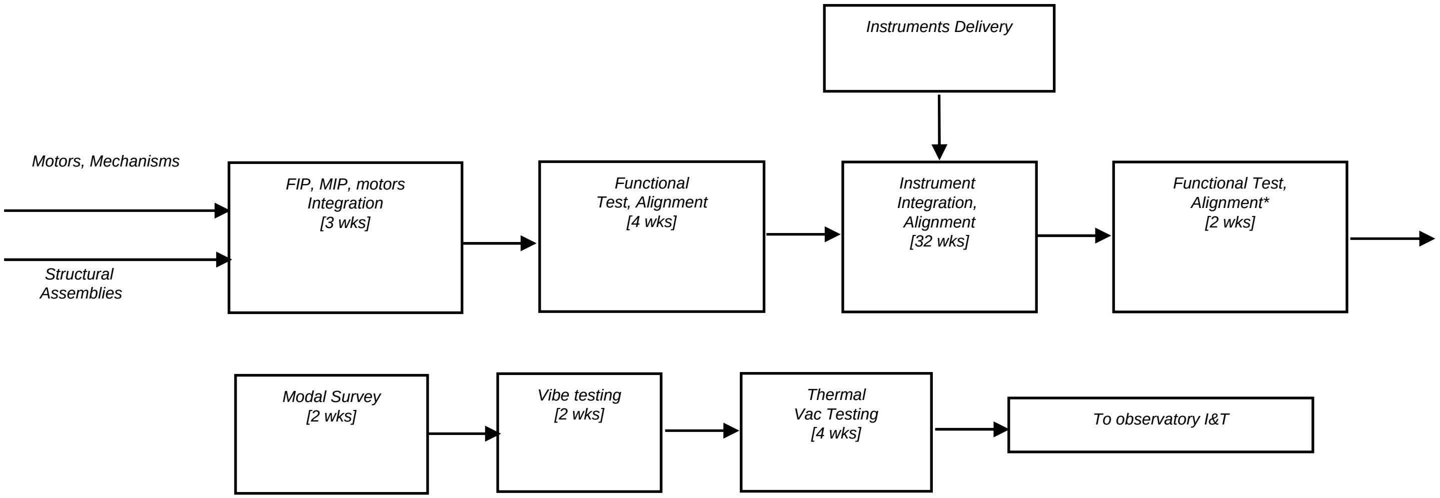
Deployment Module I&T – Top-Level Flow

- Assumptions
  - ADAMS Masts, Shroud & trays environmentally qualified.
  - Structure Strength qualified
  - All boxes environmentally qualified
    - EMI/EMC
    - Vibration
    - Thermal



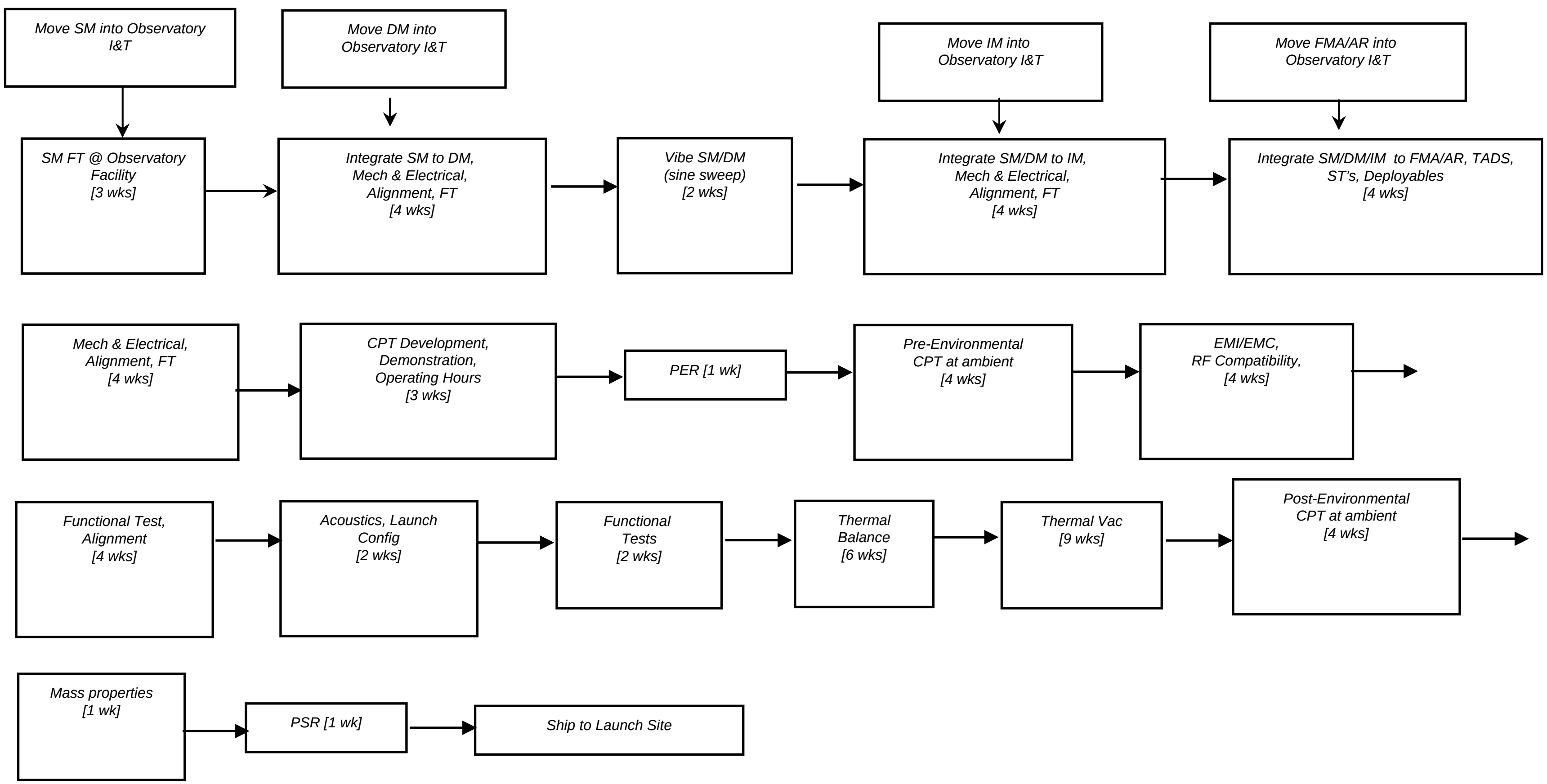
Instrument Module I&T – Top-Level Flow

- Assumptions
  - Instruments environmentally qualified.
  - Structure Strength qualified
  - All boxes environmentally qualified
    - EMI/EMC
    - Vibration
    - Thermal

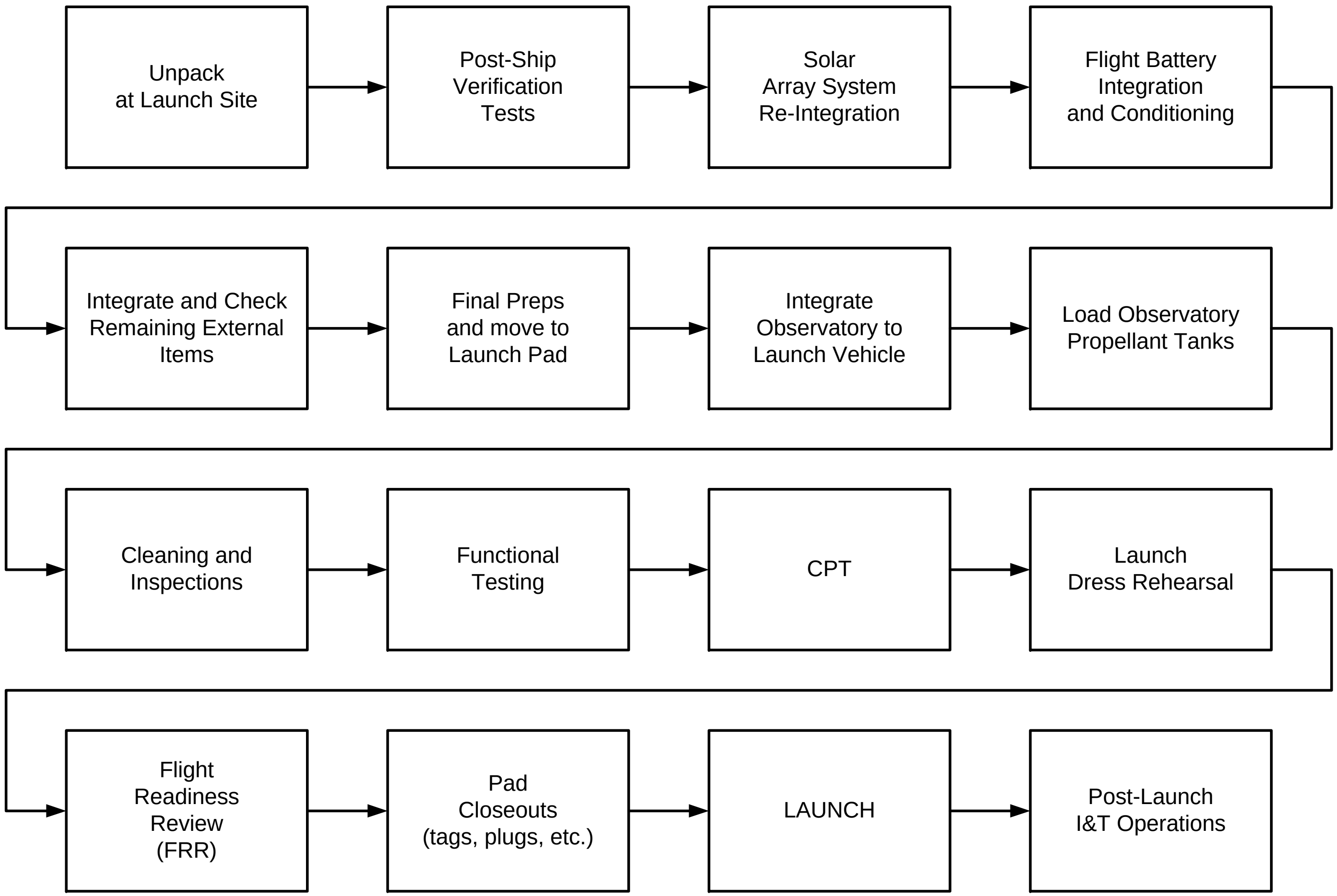


Observatory I&T – Top-Level Flow

- **Assumptions**
  - **All Modules arrive fully qualified**



Launch Site Ops



GSE Required for I&T effort

Equipment	Purpose	Provider
Electrical Ground Support Equipment (EGSE)	**Electrical control and testing of the S/C (i.e. Umbilical console)**	**Electrical Subsystem**
Spacecraft Ground Support Equipment (SGSE)	S/C command, control, and telemetry (i.e. ASIST workstations, front end data processing & distribution, archiving, other IT equipment)	I&T
Mechanical Ground Support Equipment (MGSE)	**Ground handling and transportation (i.e. Dollies, slings, access scaffolding, rotation fixtures, environmentally controlled transporter, etc.)**	**Mechanical Subsystem**
Power GSE	**Support, control and/or simulate power system components (i.e. Solar array simulator, battery simulator, battery AC, battery GSE)**	**Power Subsystem**
Alignment Ground Support Equipment (AGSE)	**Aligning spacecraft components and instrument. (i.e. Tooling bars, theodolites, levels, tilt sensors, dihedral reference mirrors, etc.)**	**Optical Branch Support**
I&T Ground Support Equipment (I&T GSE)	Assist in execution of I&T (i.e. Oscilloscopes, meters, current probes, break out boxes, ESD protective equipment, IT equipment, etc.)	I&T

NOTE: Substantial amounts of GSE are required to support the integration effort. Much of this equipment will be developed and used at the subsystem level and be delivered with the flight hardware to I&T. Other equipment will be developed specifically for I&T use. Only GSE identified in this table as being provided by I&T is included in the I&T costs. The costs for all other GSE are assumed to be carried by the group identified in the column marked "Provider." The costs and development schedule of this equipment is not trivial. This list is not meant to be exhaustive or complete.

GSE Required for I&T effort, Ct'd

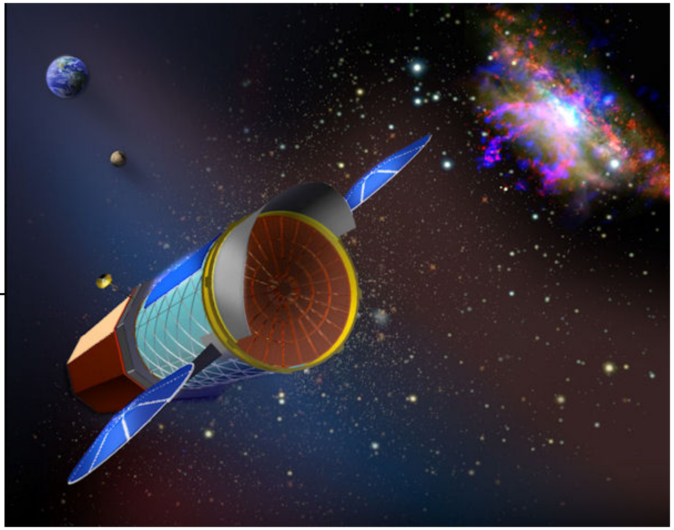
Equipment	Purpose	Provider
Command and Data Handling (C&DH) GSE	**Test and checkout the C&DH subsystem. (i.e. Timing GSE, bus monitor etc.)**	**C&DH Subsystem**
Propulsion GSE	**Testing and integrating the propulsion subsystem (i.e. propulsion system monitoring EGSE, pyro load simulator/tester, pressurization rack, propulsion system MGSE: dolly and lifting slings etc.)**	**Propulsion Subsystem (with assistance from Electrical and Mechanical)**
Deployment Ground Support Equipment (DGSE)	**Test the S/C deployment systems, Solar Array and High Gain antennas, sun shield, other covers. (i.e. G-negation systems, etc.)**	**Deployment Subsystems (with assistance from Mechanical Subsystem)**
Attitude Control System (ACS) GSE	**Stimulate and test the ACS. (i.e. Goddard Dynamic Simulator, Sun Sensor Stims, Star Tracker Stims etc.)**	**ACS Subsystem**
RF GSE	**Test the S-band and Ka-band RF Receivers and Transmitters & links (i.e. RF test racks, hat couplers, receivers, demodulators, cable & couplers etc.)**	**RF Subsystem**
Instrument Ground Support Equipment (IGSE)	**Test, stimulate, and handle the instruments during stand alone testing, and integrated testing (Command and Telemetry computers, calibration sources, MGSE, purge systems, protective covers etc.)**	**Instrument Providers**
Contamination GSE	**Monitoring and control of contamination & sources (i.e. cleanroom garb, wipes, inspection lights, vacuums, chemicals etc.)**	**Contamination Engineering**

List of Large Thermal/Vac Chambers in the US

- There are five thermal/vac chambers in the US that are large enough to accommodate the fully extended Con-X spacecraft (which is approximately 12' in diameter by 75' high):
  - Arnold Engineering Development Center, Arnold AFB, Tullahoma, Tennessee; 42' diameter by 82' high (vertical)
  - NASA JPL, Pasadena, California;
    27' diameter by 85' high (vertical)
  - NASA JSC, Houston, Texas;
    65' diameter by 120' high (vertical)
  - NASA GRC, Plum Brook Station, Sandusky, Ohio;
    100' diameter by 122' high (vertical)
  - Lockheed Martin Missiles and Space, Sunnyvale, California;
    40' diameter by 80' long (horizontal)
- There are a number of chambers in the US which could accommodate the IXO partially extended

IXO Systems Definition Document
Chapter 9

Mission Operations

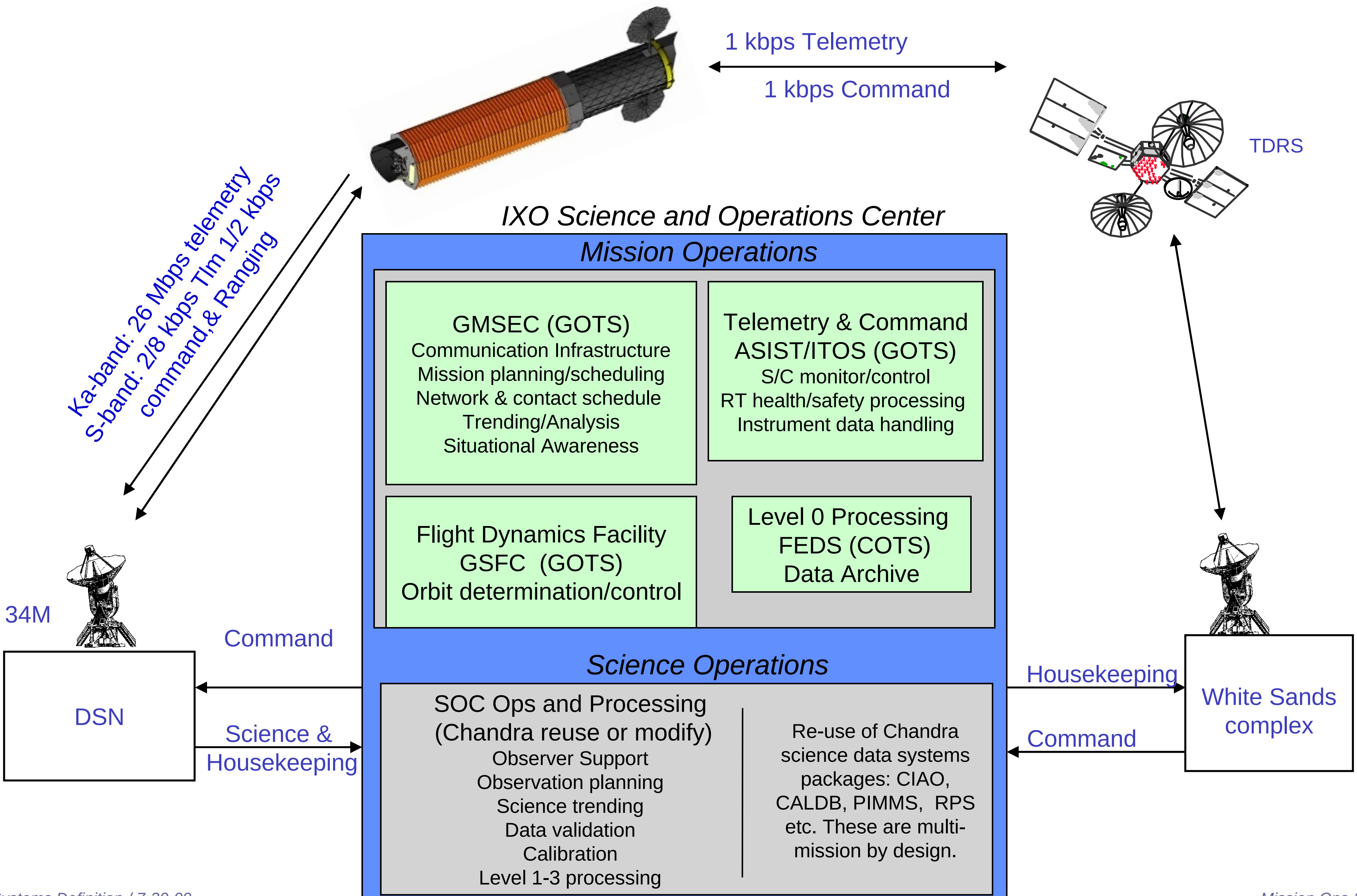


Mission Operations Overview

- **IXO will be a facility class observatory:**
  - **Programs selected via competitive Peer Review**
- **IXO operates as a queue-scheduled observatory:**
  - **Pointing at selected targets in the most time efficient way consistent with science and observatory constraints**
  - **No unusual mission or operational constraints**
  - **No unusual communication requirements**
- **Time on a target (pointings):**
  - **10^3 to 10^6 sec; observations may have several pointing intervals**
  - **1 – 20 observations per week**
- **IXO Operations Concept is well developed:**
  - **Based on the Chandra model**
  - **Updates mission operations with proven COTS and GOTS products**
  - **Re-use of existing expertise and facilities**
- **IXO MODA follows recommendations from the "Portals" NRC report**

Panoramic view of the Chandra Operations Center

IXO Functional Configuration Overview



Driving Requirements for MO&DA - I

Parameter	Requirement	Source/Rationale	Performance
Telescope pointing (aspect) determination ground-based post processed	1 arcsec, 3σ	Flow down from aspect determination error budget to meet the celestial location knowledge	Pointing budget supports achieving requirement
Telemetry Volume (normal operations)	Capable of downlinking 1 day of data per pass; 30 minutes per pass	Flow down from Ops Concept, in conjunction with onboard storage limit	Ka-band antennas and ground stations sized to meet requirements with margin
Downlink Frequency	1 downlink/day	Ops Concept: joint requirement on sizing of on-board storage	1 downlink/day
Timing	Arrival time accuracy of ±100 microseconds (UTC)	Top level requirement	Arrival time accuracy ±90 μsec
Mission Duration	5 years normal science operations	Top level requirement	Systems designed & expendables sized to meet requirement
Observing Efficiency	85%	Science Traceability Matrix to achieve all goals	Achieved via L2 orbit
Sky Coverage	100% 1x/year, 90% 2x/year	Top level requirement	Achieved via L2 orbit

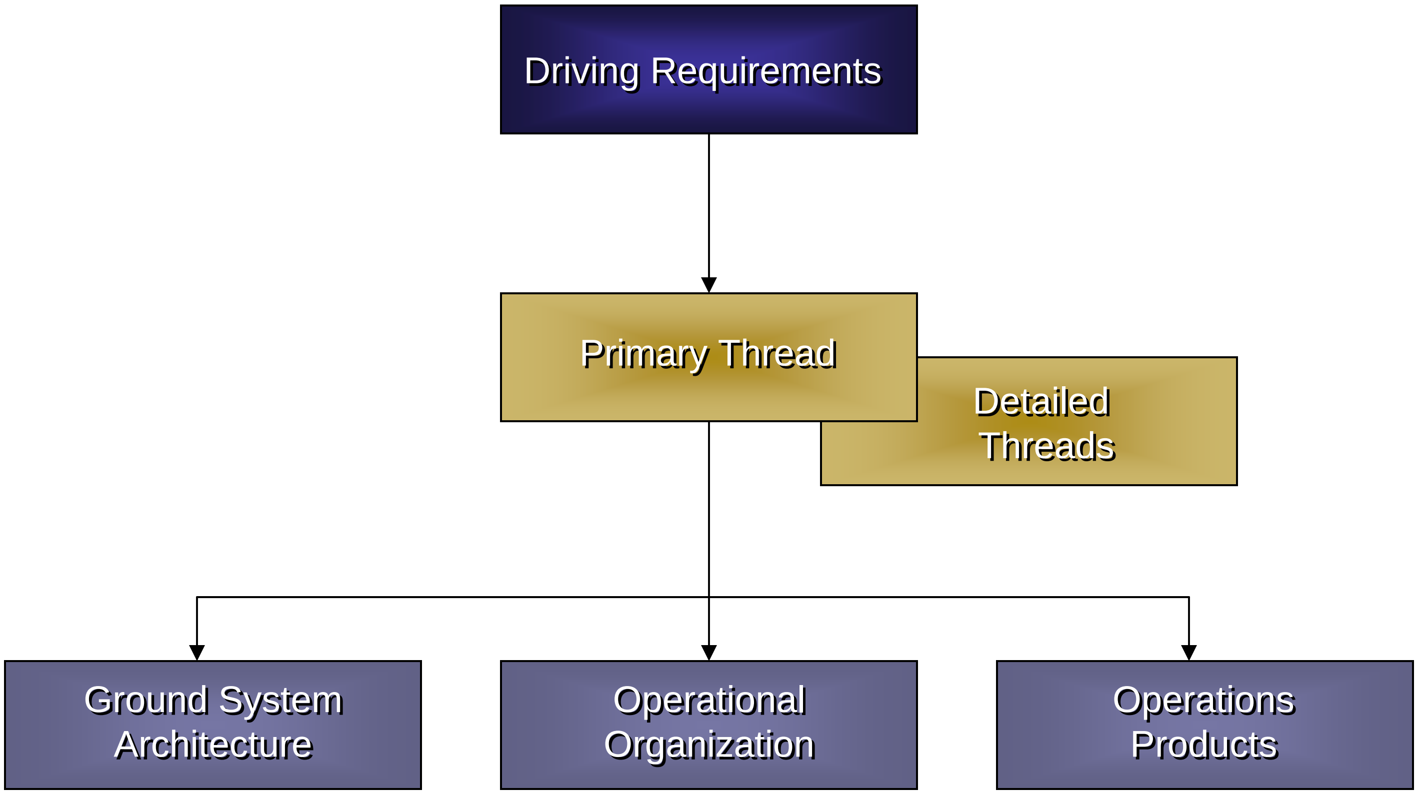
Driving Requirements for MO&DA - II

Parameter	Requirement	Source/Rationale	Performance
Data Uplink	2 kbps	Ops Concept	S-band uplink meets requirement
Data Uplink Frequency	Once/week	Ops Concept	Science Observing Plan generated and uplinked weekly
Science Data Latency	2 weeks (72-hour goal) from completion of observation to product delivery*	Top level requirement	Ground system achieves 48 hours
TOO Frequency	Approx. 2x per month	Top level requirement	Design can meet and exceed requirement
TOO Response Time	<24 hours	Top level requirement	TBD
Archive Storage	40TB to 80TB over 5 years for all raw and processed (to Level 3) mission data, including reprocessing	Derived from mission lifetime req't	Ground system archive sized to 100 TB

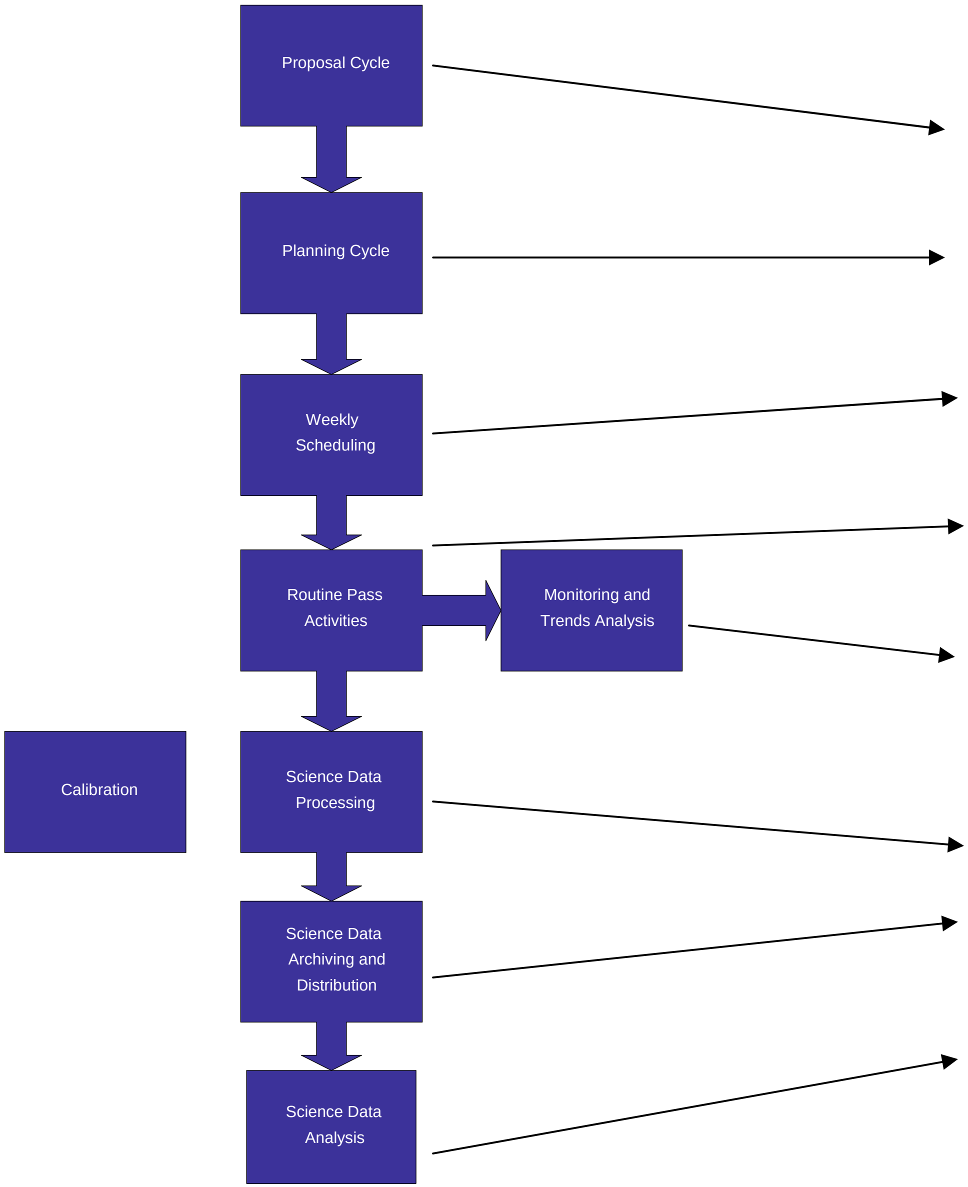
**Excludes bright source observations*

IXO Operations Concept

Significant progress has been made in identifying and documenting the IXO operations concept. The Operations Concept document forms the basis for the MO&DA components of IXO.

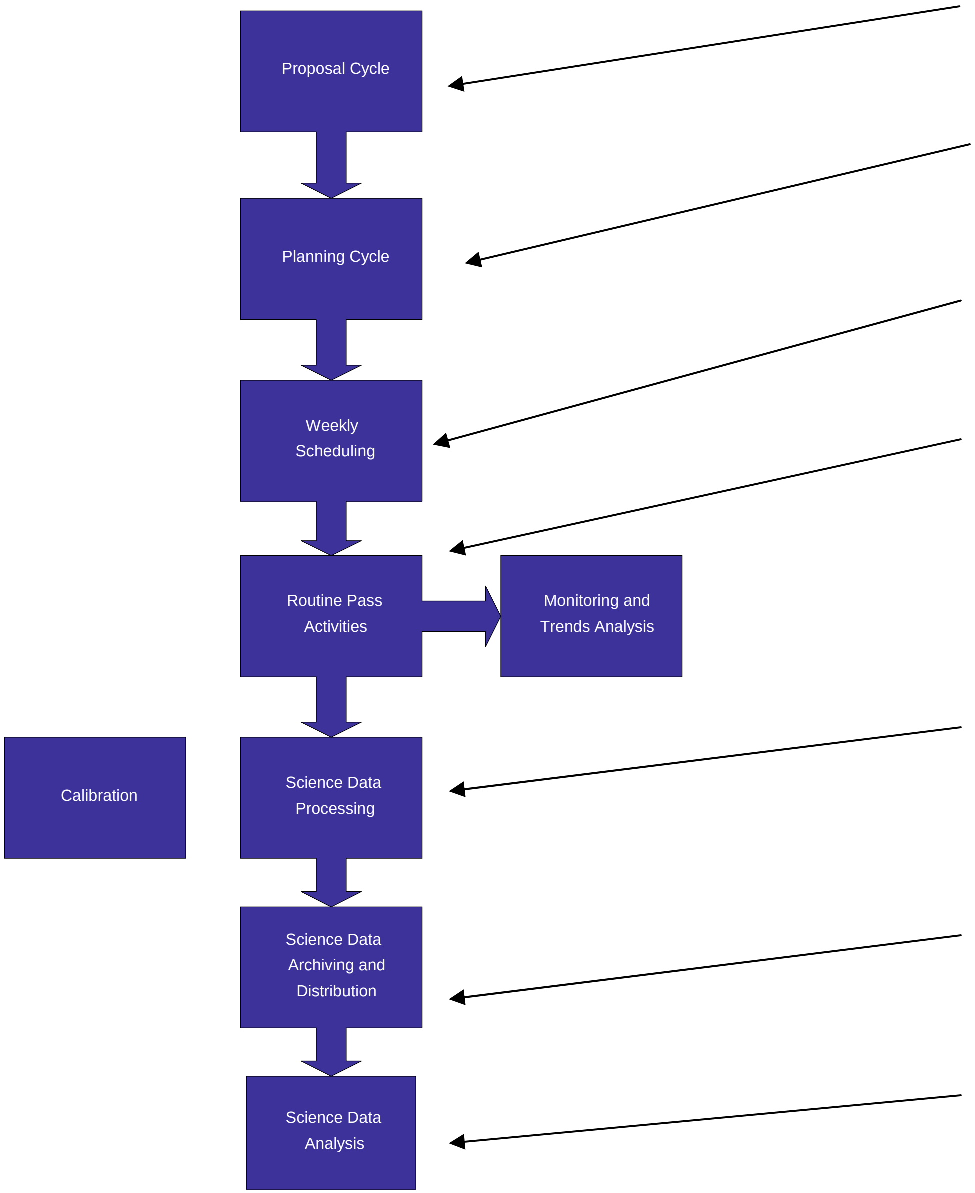


Primary Operational Thread



- Observer prepares and submits proposal
- Generate long-term science plan
- Flight mission planning cycle, generate command loads
- Uplink, tracking, on-board activities, downlink
- Engineering and Science Instrument monitoring and analysis
- Level 0 to 3
- Science Archiving, data distribution, web access
- Analysis tools, documentation, cook-book recipes

Primary Operational Thread and Driving Requirements



- Mission Duration
- Observing Efficiency
- Sky Coverage

- Observing Efficiency
- Sky Coverage
- TOO Frequency
- Calibration requirements

- Uplink Frequency
- TOO Frequency
- TOO Response Time

- Downlink Frequency
- Telemetry Volume
- Timing
- Uplink Frequency
- Uplink Volume
- TOO Response Time
- Data Latency

- Telescope Pointing
- Telemetry Volume
- Timing
- Data Latency
- Archive Storage

- Mission Duration
- Telemetry Volume
- Data Latency
- Archive Storage

- Telescope Pointing
- Sky Coverage
- Timing

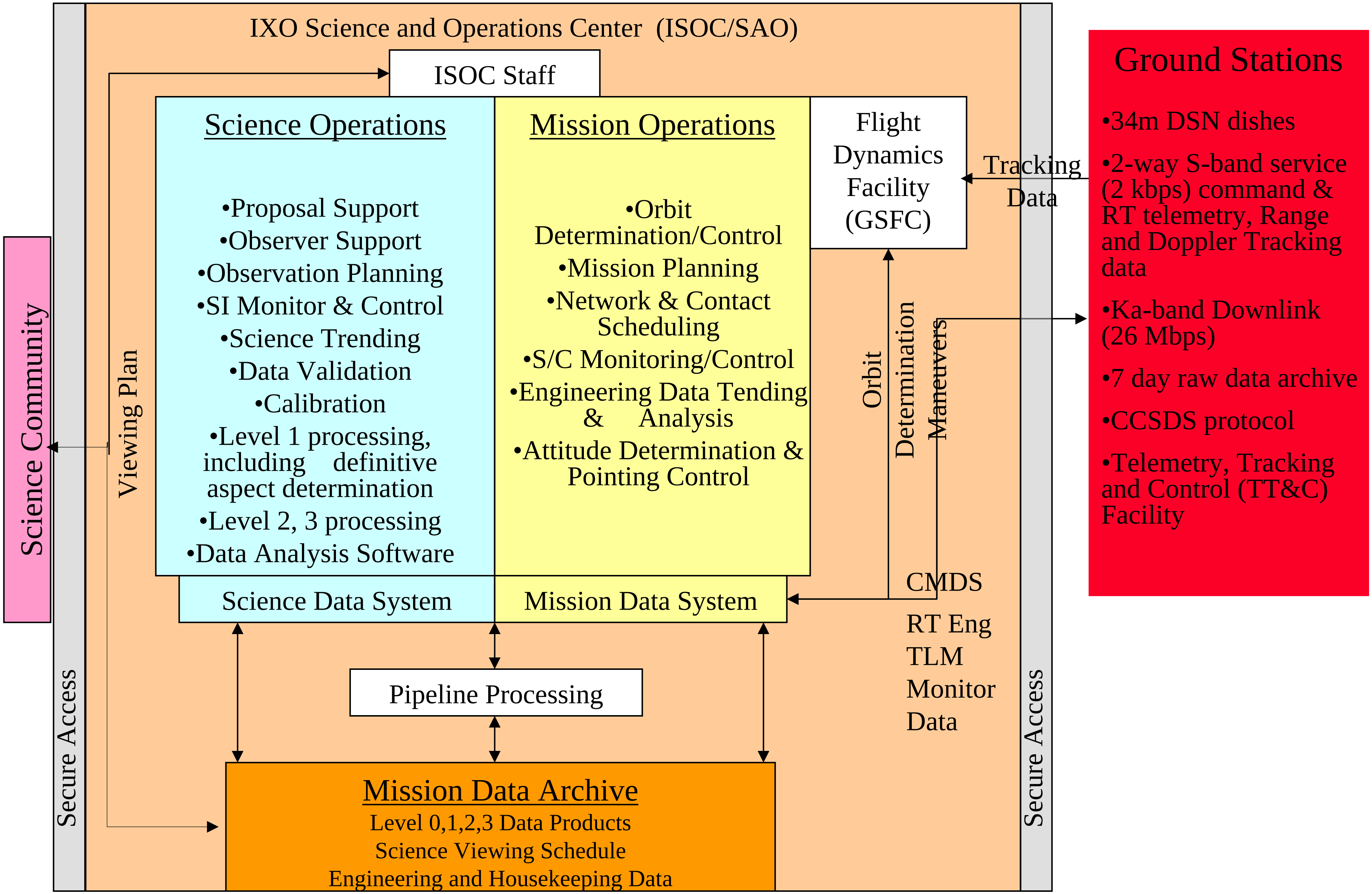
Detailed Operational Threads

- Peer Review
- Science Planning and Scheduling
- Contact Planning and Scheduling
- Momentum Management
- High-Gain Antenna Management
- Routine Pass Activities
- Spacecraft Health and Safety Monitoring
- Instrument Performance Monitoring
- Trending
- Time Management
- Orbit Determination
- Science Data Processing
- Science Data Archiving and Distribution
- Science Data Analysis
- Calibration
- Target of Opportunity
- Flight Software Maintenance
- Reduced Aperture Operations
- Radiation Operations
- On-Board Recorder Management

ISOC – Key Functions and Services

- Phase CD:
  - Develop observatory calibration plan including optics, instruments.
  - Flows calibration requirements to instrument & optics teams
  - Supports instrument and observatory I&T
  - Pre-launch data flow development, science analysis software development, etc…
- Phase E:
  - Flight operations support
  - Instrument operations and calibration
  - Data V&V
  - Data analysis
  - Distribution and archiving of data and data products
  - Help desk and user support services
  - Proposal submission processing and peer review evaluations
  - Software development and documentation for science analysis
  - Scientific research
  - Grants management and administration
  - Education and public outreach

IXO Operations Concept Reference Architecture



Mission Data System

The Mission Data System (MDS) consists of proven COTS and GOTS products that perform all traditional mission data processing functions for the spacecraft platforms and for science instrument health and safety. The MDS consists of the data system resources required for:

GOTS Packages	Functions
Asist or ITOS	
	S/C monitoring & Control
	R/T health/safety processing for s/c & instruments
	Instrument data handling
GMSEC	
	Comm infrastructure
	Observatory planning/scheduling
	Network & contact scheduling
	Trending/Analysis
	Situational Awareness
Flight Dynamics Facility	
	Orbit determination/control

COTS Packages	Functions
FEDS	
	Level 0 Data Processing

Science Data System

The Science Data System (SDS) consists of the data system processing, storage, and long term archiving resources required for:

- **Science observation planning.**
- **Science data processing (including pipeline processing of these data using algorithms provided by the Science Instrument Operations Teams) including science data calibration and validation.**
  - **Level 1 to 3 processing.**
- **Management of and accountability for all data (telemetry, ancillary, and products).**
- **Building, validating, and distributing the software necessary to analyze the observation data at the NASA, ESA, and JAXA SOCs and investigator's home institutions.**
- **Distribution of these data as requested by the observer, ISOC staff, and SI teams.**
- **Dissemination of public data.**

SDS Data Analysis Software System

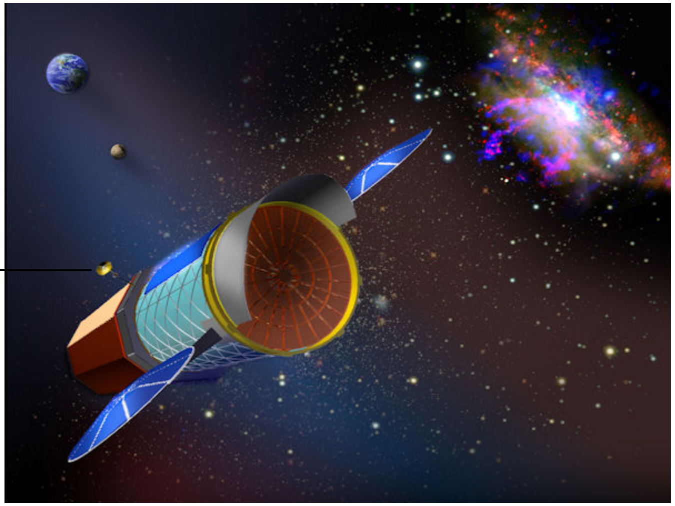
- CIAO is a data analysis system written for the Chandra X-ray Observatory and is easily extensible to IXO. Because X-ray data is 4-dimensional (2 spatial, time, energy) and each dimension has many independent elements, CIAO was built to handle N-dimensional data without concern about which particular axes were being analyzed. *CIAO is mission independent by design.*
- CIAO can perform X-ray imaging, spectral, and timing analysis as well as combinations of these three.
  - Only new modules required are for X-ray polarimetry data.
- CIAO includes:
  - SHERPA:
    - Sherpa has extensive facilities for modeling and fitting X-ray data. This includes basic fits using source spectra and responses to more advanced areas such as simultaneous fits to multiple data sets, accounting for the effects of pileup, and fitting spatial and grating data.
    - Sherpa (using CHIPS, see below) allows the user to plot data, fits, statistics, effective areas, contours, and more.
    - Sherpa determines goodness of fit, errors in parameter values, confidence intervals, and other statistical measures of a model's validity.
    - Sherpa simulates X-ray data given an input instrument response and source model expression.
  - CHIPS:
    - Provides high-quality screen and hardcopy plots from both interactive and scriptable interfaces using Python.

SDS Calibration Software System

- The CALDB (CALibration DataBase) stores and provides access to the calibration files needed for standard processing and analysis. These files can be accessed with software packages such as CIAO.
- *The CALDB is multi-mission by design* and will support IXO calibration file storage and access.
- The CALDB:
  - Stores and archives calibration files.
  - Maintains a naming convention and header structure for all calibration files.
  - Indexes calibration data, based on FITS keywords, for software access.
  - Permits updates independent of software updates, while maintaining configuration control.
  - Provides a traceable history of calibration data in the database.
  - Translates calibration products into formats suitable for processing and/or analysis

IXO Systems Definition Document Appendix

Payload Overview



Precedence

- **The controlling payload interface and accommodation requirements which IXO was designed to meet are documented in the IXO Systems Spreadsheet**
  – To avoid any conflict with the Payload PDDs, this Appendix is non-controlling, and is to be used for general information purposes only

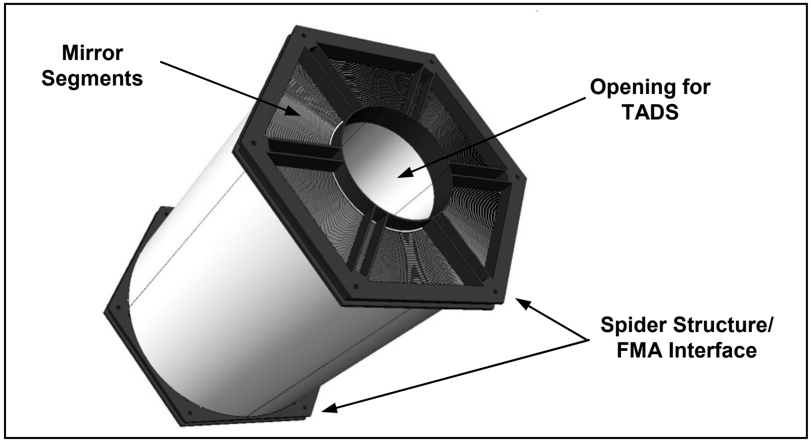
FMA

FMA Subsystems

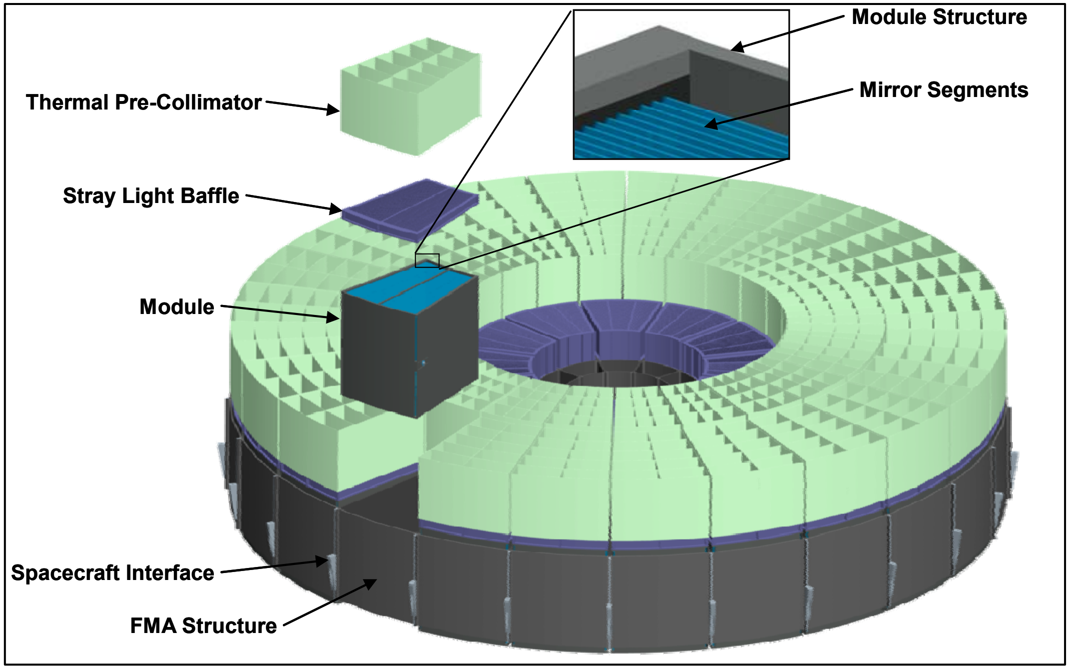
- **Optical Subsystem:**
  - Soft X-Ray Telescope (SXT)
    - Primary mirror segments
    - Secondary mirror segments
    - Stray Light Baffles *
  - Hard X-Ray Mirror Module (HXMM)
- **Mechanical Subsystem:**
  - Module structure
  - FMA structure
- **Thermal Subsystem:**
  - Thermal Pre-Collimators *
  - Thermal Shields
  - Heaters/Harnesses

** Components that have shared Optical/Thermal attributes*

HXMM Configuration

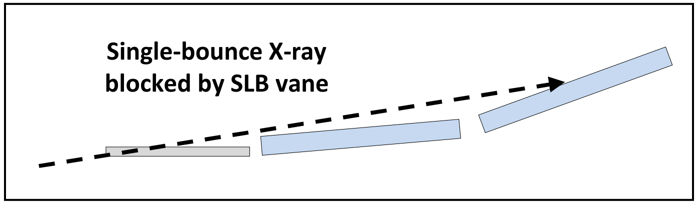


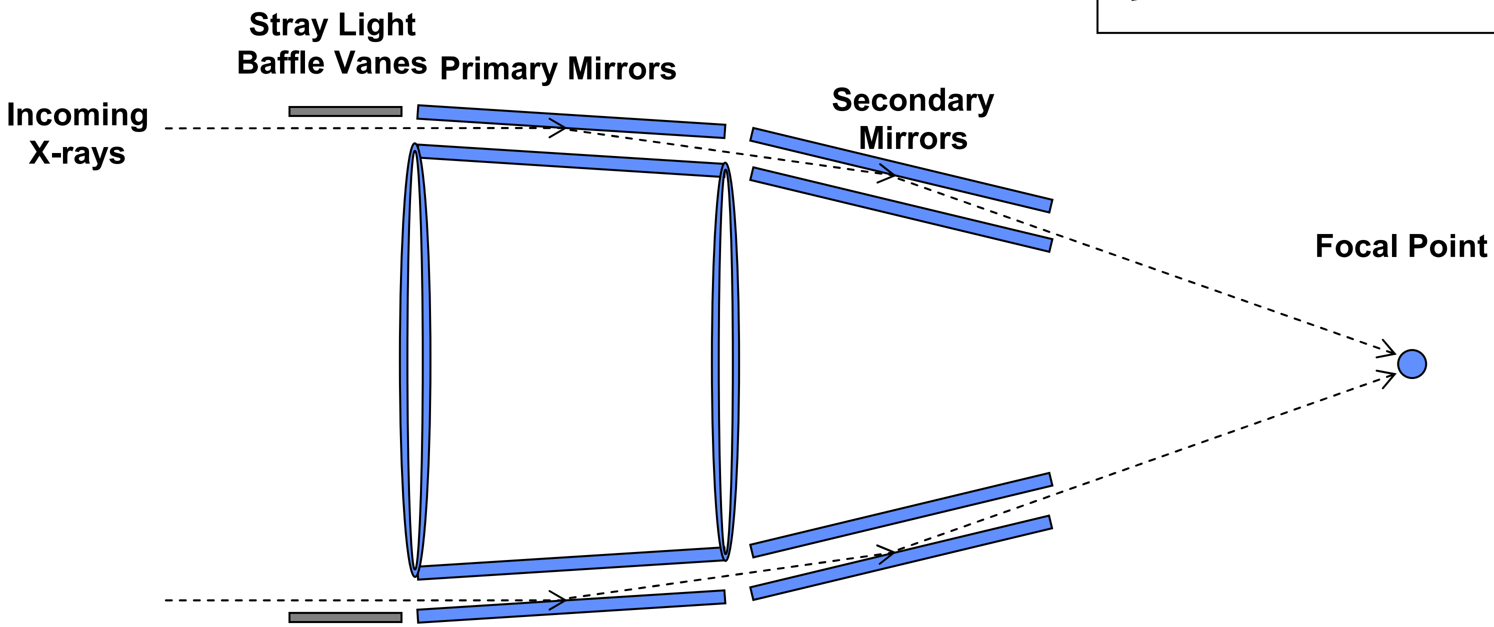
SXT Configuration



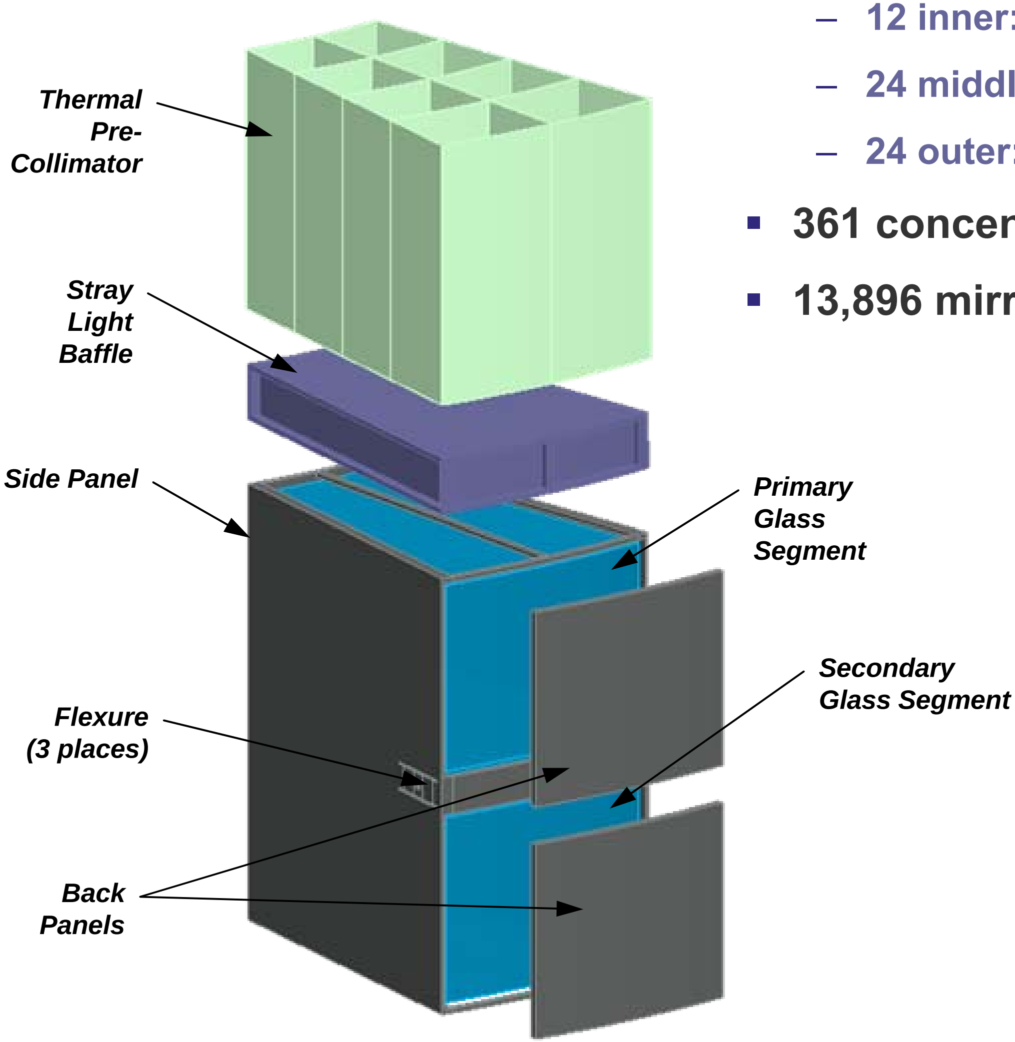
X-Ray Optic Primer

- Highly nested grazing incidence optics
  - If angle of incidence is too high, x-ray will be absorbed
  - Critical angle is dependent on energy of x-ray
- X-rays are focused by a primary and a secondary mirror
- Shells packed to increase collecting area
- Segmented mirror design



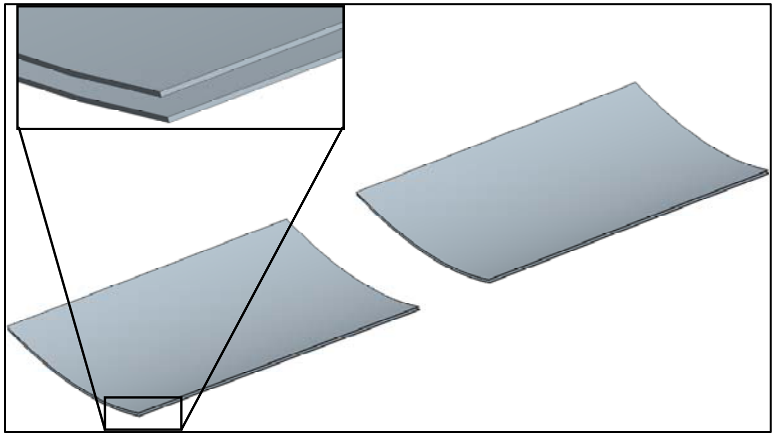


SXT Mirror Module



- Modular design: 60 modules
  - 12 inner: 143 mirror pairs
  - 24 middle: 115 mirror pairs
  - 24 outer: 103 mirror pairs
- 361 concentric shells (pairs)
- 13,896 mirror segments

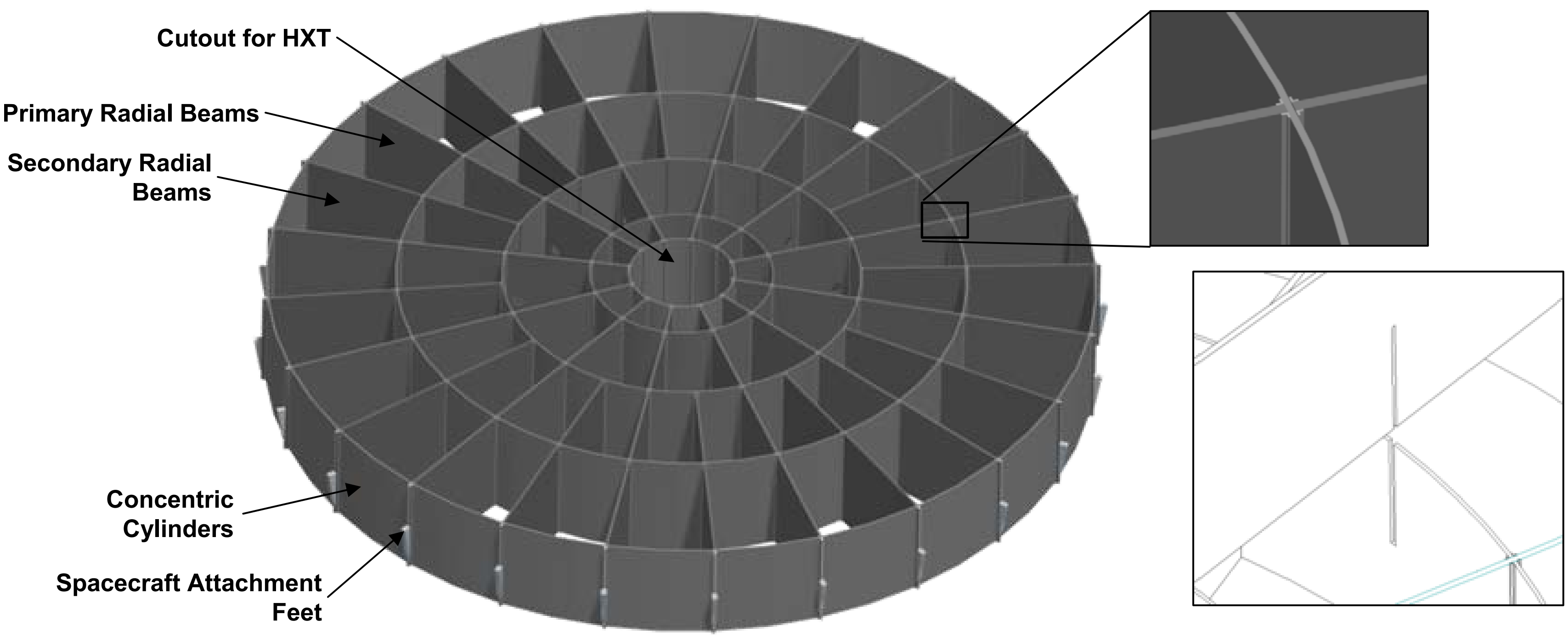
SXT Glass Mirror Segment



Nested Mirror Segments

FMA Primary Structure

- Carrier structure supporting 60 kinematically mounted modules totaling ~1300 kg
- Constructed using standard aerospace materials and design practices
- All structural members made from M55J/954-3 Carbon Fiber Reinforced Plastic (CFRP) for high stiffness, low weight, and near-zero CTE
- Primary and secondary radial beams of rectangular cross sections
  - Minimizes beam thickness and maximizes effective area
- Radial beams connected by concentric cylinders
- Bonded ‘wine-box’ construction with doublers in corners



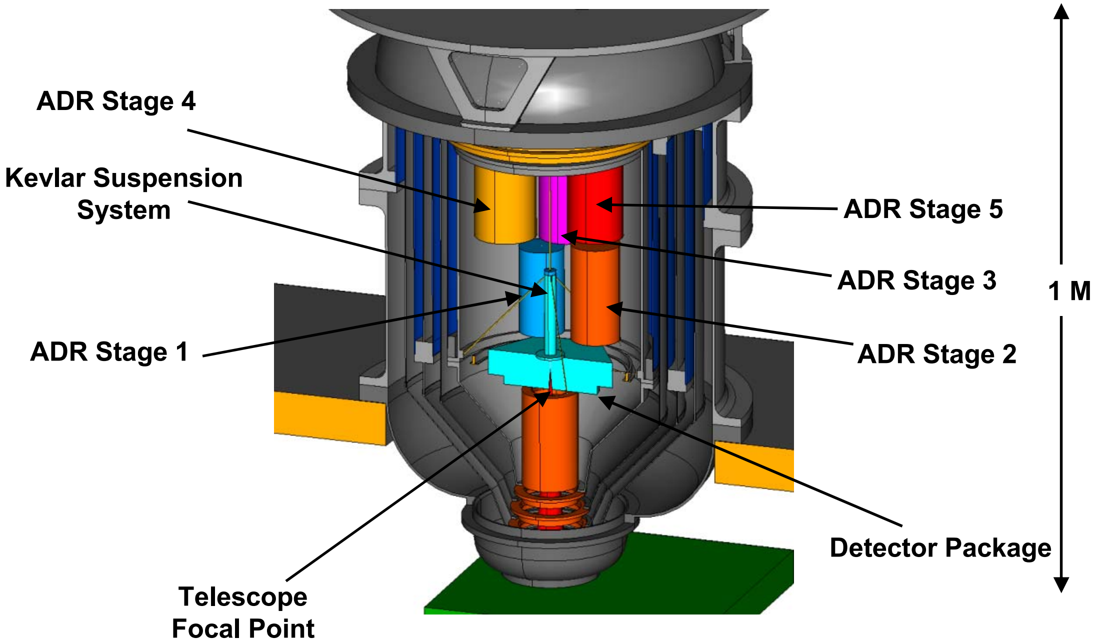
XMS

X-ray Microcalorimeter Spectrometer (XMS)

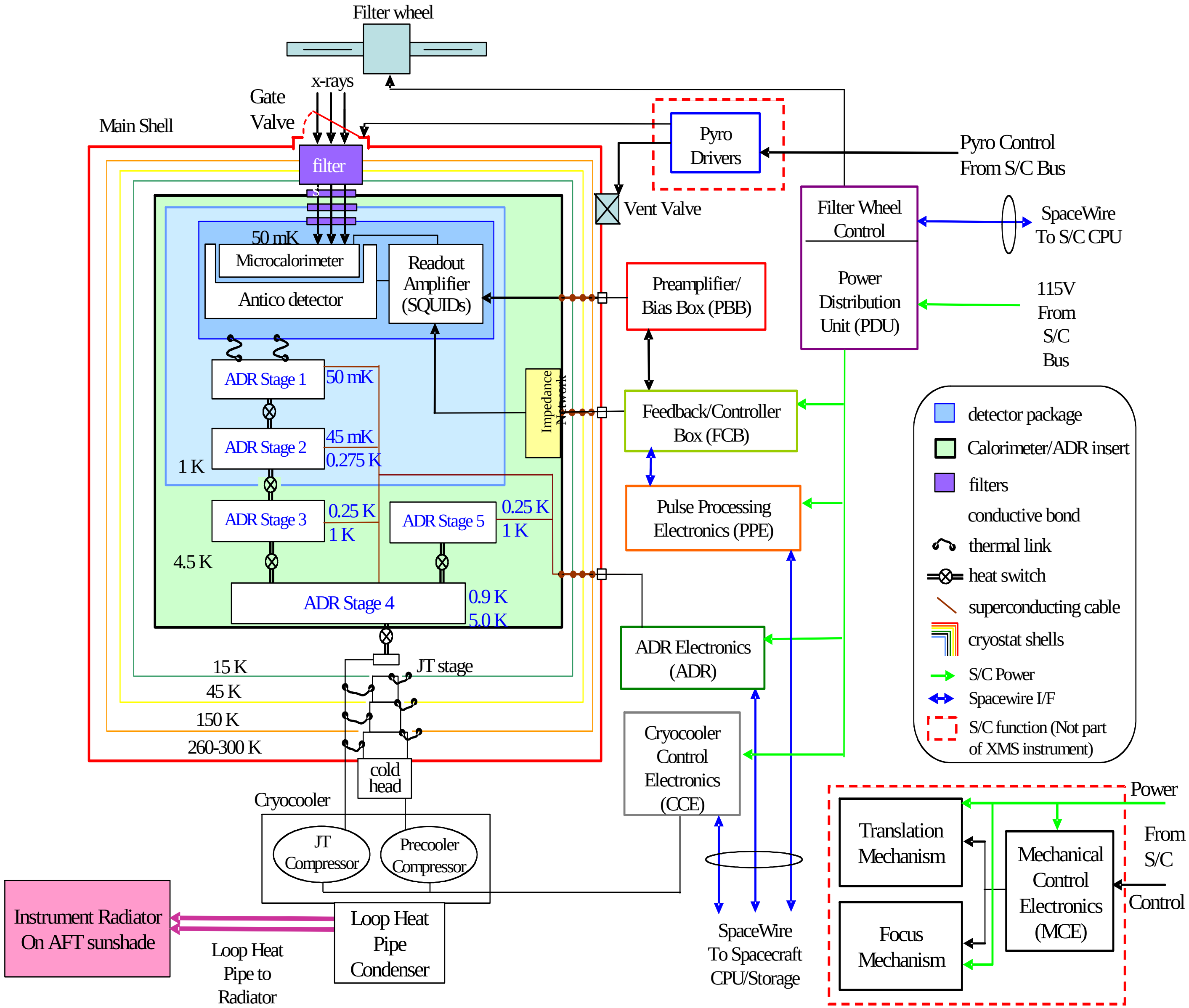
- **Imaging Spectrometer:**

- **Key Performance Requirements**
  - Bandpass: 0.6 to 10 keV
  - Spectral Resolution:
    - 2.5 eV < 6keV for FOV 2 arcmin
    - 10 eV < 6kev for FOV 5.4 arcmin

- **Features**
  - Transition Edge Sensor microcalorimeter
  - Array size configured with:
    - 2 arcmin inner "high resolution" array, 40x40 pixels @ 300µm pixel size
    - 5.4 arcmin "extended field" array
  - Photon counting device
  - Detector operates at 50 mK
    - Cooled by multistage ADR in series with mechanical cryocooler
    - No expendable cryogens
  - Data Rate: 29.6kbps (ave), 1684 kbps (peak)



XMS Functional Block Diagram



XMS Mechanical Interface Requirements*

Mechanical Interface Requirements (Current Best Estimate - No Margin)				
Payload Element		**Dimen (cm) H x W x D**	**Location**	**Comments / Source**
XMS	Dewar Assembly	100x75 Dia	At FMA focus, on MIP	Include cryocooler and compressor
	Filter Wheel	21X64X40	Mounted to dewar shell, forward end	
	Pre-Amplifier/BiasBox (PBB)	15x23x20	<1 m from dewar	
	Feedback/Controller Box (FCB) -1	23x28x20	<1 m from dewar	
	Feedback/Controller Box (FCB) -2	23x28x20	<1 m from dewar	
	Feedback/Controller Box (FCB) -3	23x28x20	<1 m from dewar	
	Feedback/Controller Box (FCB) -4	23x28x20	<1 m from dewar	
	Pulse Processing Electronics (PPE)	28x28x20	<several m from dewar	
	ADR Controller (ADRC)	13x25x38	<several m from dewar	
	Cryocooler Control Electronics (CCE)	20x20x20	<several m from dewar	2 cards 1 box
	Filter Wheel Control Electronics (FWC)	25x20x5	<several m from dewar	
	Power Distribution Unit (PDU) -1	25x38x20	<several m from dewar	
	Power Distribution Unit (PDU) -2	20x38x20	<several m from dewar	

Harness mass included in observatory harness mass

XMS Thermal Interface Requirements

Instrument Thermal Interface Requirements					
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**	**Comments / Source**
XMS	Dewar Assembly	-33C to 27C		-100C to 50C	**CDF = 20C**
	Filter Wheel	-20C to 50C		-20C to 50C	
	Pre-Amplifier/BiasBox (PBB)	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -1	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -2	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -3	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -4	-20C to 50C		-30C to 70C	
	Pulse Processing Electronics (PPE)	-20C to 50C		-30C to 70C	
	ADR Controller (ADRC)	7C to 27C		-30C to 70C	
	Cryocooler Compressor	10C to 40C		-20C to 50C	
	Cryocooler Control Electronics (CCE)	10C to 40C		-30C to 70C	
	Filter Wheel Control Electronics (FWC)	10C to 40C		-30C to 70C	
	Power Distribution Unit (PDU) -1	10C to 40C		-30C to 70C	
	Power Distribution Unit (PDU) -2	10C to 40C		-30C to 70C	

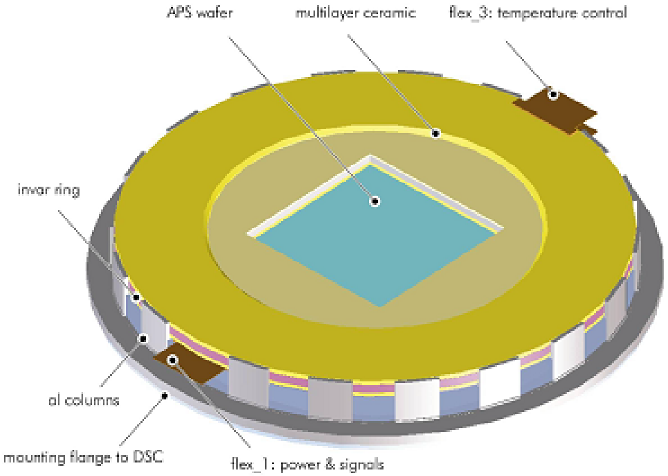
XMS Power Interface Requirements

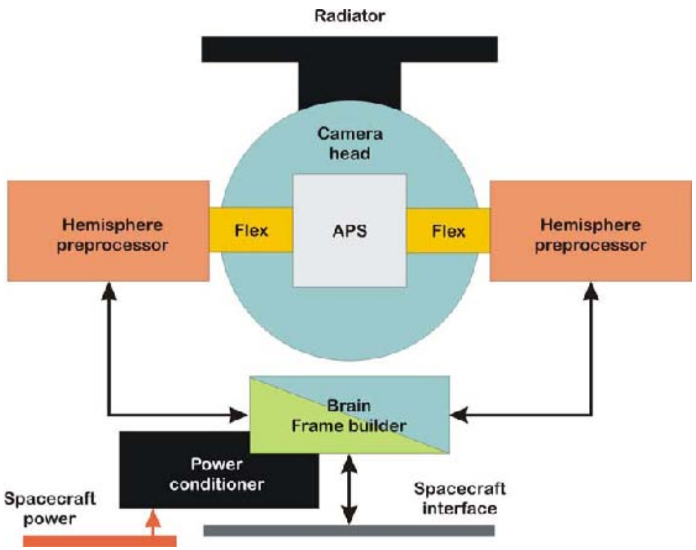
Instrument	Element	Power (W) Average	Peak	Annealing	Standby - Sleep	Safe Hold - Off	Comments /Source
	Instrument Power Interface (Current Best Estimate - No Margin)						
XMS	Dewar Assembly	215.0	215.0	0.0	215.0	0.0	Include cryocooler and compressor
	Pre-Amplifier/BiasBox (PBB)	24.8	24.8	0.0	0.0	0.0	
	Feedback/Controller Box (FCB) -1	45.0	55.0	0.0	0.0	0.0	
	Feedback/Controller Box (FCB) -2	45.0	55.0	0.0	0.0	0.0	
	Feedback/Controller Box (FCB) -3	45.0	55.0	0.0	0.0	0.0	
	Feedback/Controller Box (FCB) -4	45.0	55.0	0.0	0.0	0.0	
	Pulse Processing Electronics (PPE)	62.0	62.0	0.0	0.0	0.0	
	ADR Controller (ADRC)	5.0	8.0	0.0	0.0	0.0	
	Cryocooler Control Electronics (CCE)	54.0	54.0	0.0	54.0	0.0	
	Filter Wheel Control Electronics (FWC)	0.0	2.0	0.0	0.0	0.0	
	Total (before power losses) for PDU 1	266.8	306.8	0.0	0.0	0.0	Includes PBB, FCB-1 - 4, PPE
	Total (before power losses) for PDU 2	274.0	279.0	0.0	269.0	0.0	Includes dewar, ARDC, CCE
	Power Distribution Unit (PDU) -1	53.4	61.4	0.0	0.0	0.0	Dissipation for 80% eff.
	Power Distribution Unit (PDU) -2	54.8	55.8	0.0	53.8	0.0	Dissipation for 80% eff.
	Total XMS	**649.0**	**703.0**	**0.0**	**322.8**	**0.0**	

WFI / HXI

Wide Field & Hard X-Ray Imager (WFI/HXI)

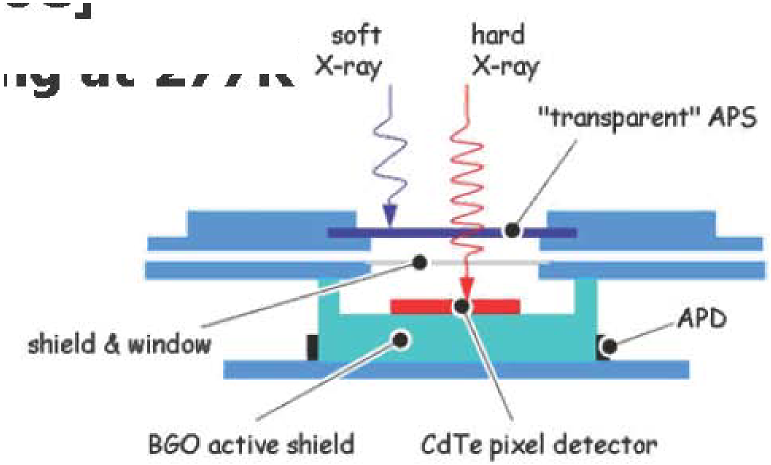
- Two Imaging spectrometers
- Key Performance Requirements
  - WFI Bandpass: 0.1 to 15 keV
  - WFI Field of View: 18 arcmin circular
  - HXI Extends Bandpass to 40 keV
  - HXI Field of View: 8 arcmin circular
- WFI Features
  - Silicon array of Active Pixels
  - Single chip 1024 x 1024; pixel pitch 100 um
  - Array size 102 x 102 mm2
  - Individual pixel access
  - Detector temperature -63 C ± 0.1 C
  - Data Rate: 45.2 kbps (ave); 1000.2 (peak)

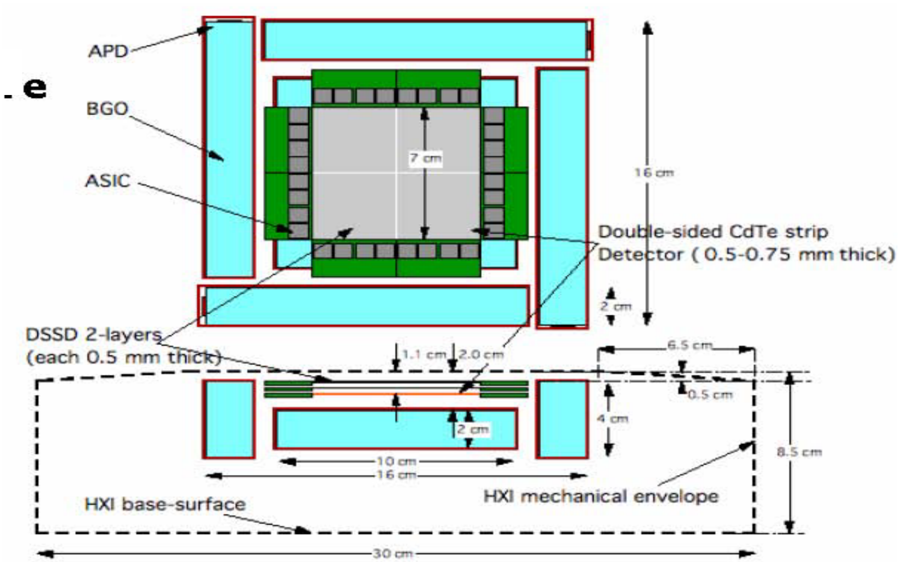




WFI / HXI Cont.

- **HXI Features**
  - Based on Si + CdTe double sided strip detectors
  - Mounts behind WFI detector within WFI envelope
  - Detector temperature: -20 C ± 2 C
  - Requires regular annealing at 5 ± 2 C
  - Data Rate: 10.8 kbps (ave); 1000.8 kbps (peak)
  - Room temperature electronics
  - Baffle required





WFI / HXI Mechanical Interface Requirements

Mechanical Interface Requirements (Current Best Estimate - No Margin)				
Payload Element		**Dim (cm) H x W x D**	**Location**	**Comments / Source**
(WF&HX)I	Focal Plane Assembly [(WF&HX)I-FPA]	21.5x32x70	On MIP - detector at mirror focus	Mass includes camera head (with radiation shield, cables, door and interfaces to radiator), filter sled and flex brackets. Baffle required
	HXI Sensor Head (HXI-S)	30x30x8.5	On MP _ Within WFI assembly (behind and coaligned with WFI)	
	Cold Part (-63C)			
	Warm Part (17 C)			Flex Brackets (2)
	WFI Hemisphere Pre-Processor-1	35x25x25	On MIP < several meters from Camera Head	2 modules, one for each hemisphere (includes boxes).
	WFI Hemisphere Pre-Processor-2	35x25x25	On MIP < several meters from Camera Head	2 modules, one for each hemisphere (includes boxes).
	HXI Analog Electronic Unit (HXI-EA)	20x20x10	On MIP < 10cm from focal plane	
	Sub-Total MIP			
	WFI Brain Frame Builder-1&2	35x50x25	On FIP < several meters from Camera Head	2 redundant modules, (included in single box)
	WFI Power Conditioner-1	35x25x25	On FIP < several meters from Camera Head	
	WFI Power Conditioner-2	35x25x25	On FIP < several meters from Camera Head	
	HXI Digital Electronics (HXI-DE)	20x20x10	On FIP < 100cm from focal plane	
	HXI PSU (HXI PSU)	20x20x10	On FIP < 100cm from focal plane	

WFI / HXI Thermal Interface Requirements

Instrument Thermal Interface Requirements					
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**	**Comments / Source**
(WF&HX)I	Focal Plane Assembly [(WF&HX)I-FPA]				
	Focal Plane Assembly - cold part	-63 +/- 0.1 C		-103 to 77 C	Thermal isolation required between camera and deck. Cooling is assumed to be through cold finger to radiator + local heater regulator. Provide 10C colder interface for detector (i.e. -73 C)
	Focal Plane Assembly - warm part	0 to 40 C		-40 to +85 C	Flex Brackets (2)
	HXI Sensor Head (HXI-S)	-20 +/- 2 C	5 ±2 C	-40 to +40 C	Internal to WFI-FPA - Set by Instrument
	WFI Hemisphere Pre-Processor-1	0 to 40 C		-40 to +85 C	
	WFI Hemisphere Pre-Processor-2	0 to 40 C		-40 to +85 C	
	HXI Analog Electronic Unit (HXI EA)	0C to 40 C	0C to 40 C	-40 to +40 C	
	WFI Brain Frame Builder-1&2	0 to 40 C		-40 to +85 C	
	WFI Power Conditioner-1 (control)	0 to 40 C		-40 to +85 C	
	WFI Power Conditioner-2 (control)	0 to 40 C		-40 to +85 C	
	HXI Digital Electronics (HXI DE)	0C to 40 C	0C to 40 C	-40 to +40 C	
	HXI PSU (HXI PSU)	0C to 40 C	0C to 40 C	-40 to +40 C	

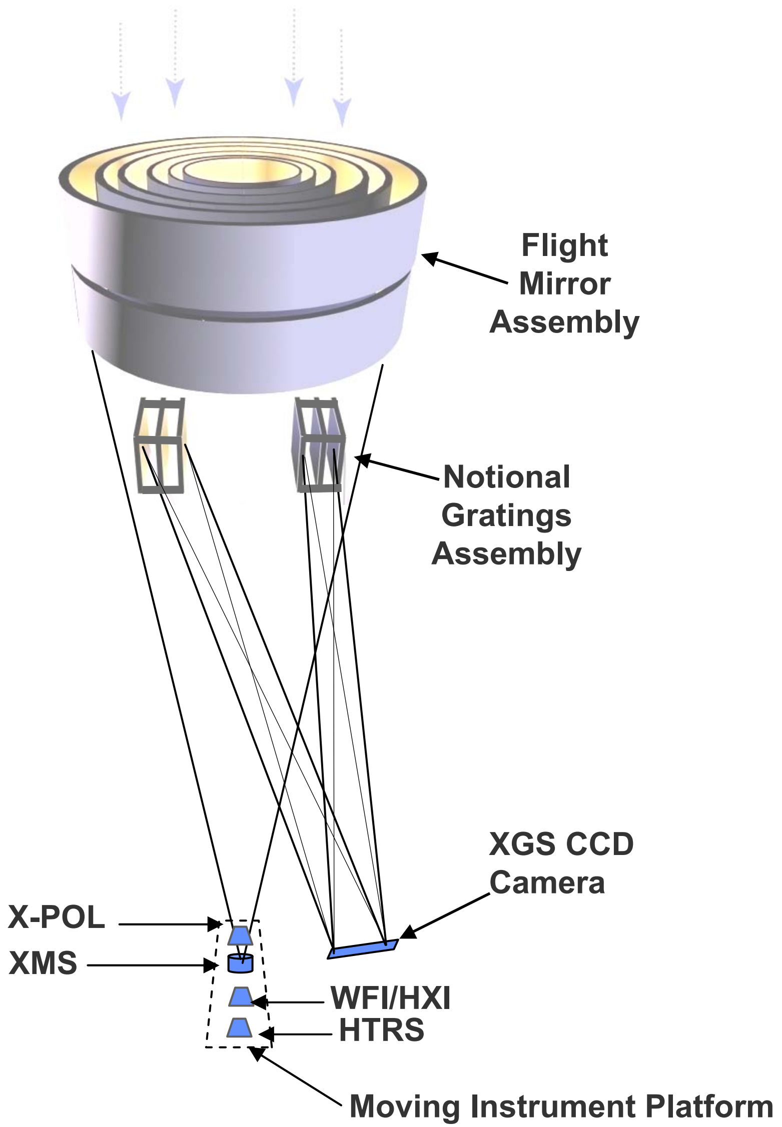
WFI / HXI Power Interface Requirements

Instrument Power Interface (Current Best Estimate - No Margin)							
Instrument	**Element**	**Power (W)**					**Comments /Source**
		Average	**Peak**	**Annealing**	**Standby - Sleep**	**Safe Hold - Off**	
(WF&HX)I	Focal Plane Assembly (FPA)						Includes camera head (with radiation shield, cables, door and interfaces to radiator), filter sled and flex brackets.
	Cold Part	25.1	25.1			0.0	
	Warm Part	18.1	18.1			0.0	
	HXI Sensor Head (HXI-S)	4.2	4.2	25.0	3.5	0.0	
	Sub-Total (FPA)	**47.3**	**47.3**	**25.0**	**3.5**		
	WFI Hemisphere Pre-Processor-1 (WFI-HPP1)	47.0	47.0			0.0	Includes ADC cluster
	WFI Hemisphere Pre-Processor-2 (WFI-HPP2)	47.0	47.0			0.0	Includes ADC cluster
	HXI Analog Electronic Unit (HXI EA)	10.8	10.8	10.8	0.0	0.0	
	Sub-Total MIP	**104.8**	**104.8**	**10.8**	**0.0**		
	WFI Brain/Frame Builder-1&2	20.0	20.0		12.0	0.0	Includes image controller
	WFI Power Conditioner-1 (WFI-PCU1)	75.9	75.9		13.7	0.0	Conversion losses for 30% eff. Dc-dc conversion
	WFI Power Conditioner-2 (WFI-PCU2)	0.0	0.0		0.0	0.0	Redundant Unit - Conversion losses for 30% eff. Dc-dc conversion
	HXI Digital Electronics (HXI DE)	7.5	7.5	7.5	0.0	0.0	
	HXI PSU (HXI PSU)	13.3	13.3	22.3	1.0	0.0	
	Sub-Total FIP	**116.8**	**116.8**	**29.8**	**26.7**	**0.0**	
	Total (WF&HX)I	**268.9**	**268.9**	**65.6**	**30.2**	**0.0**	

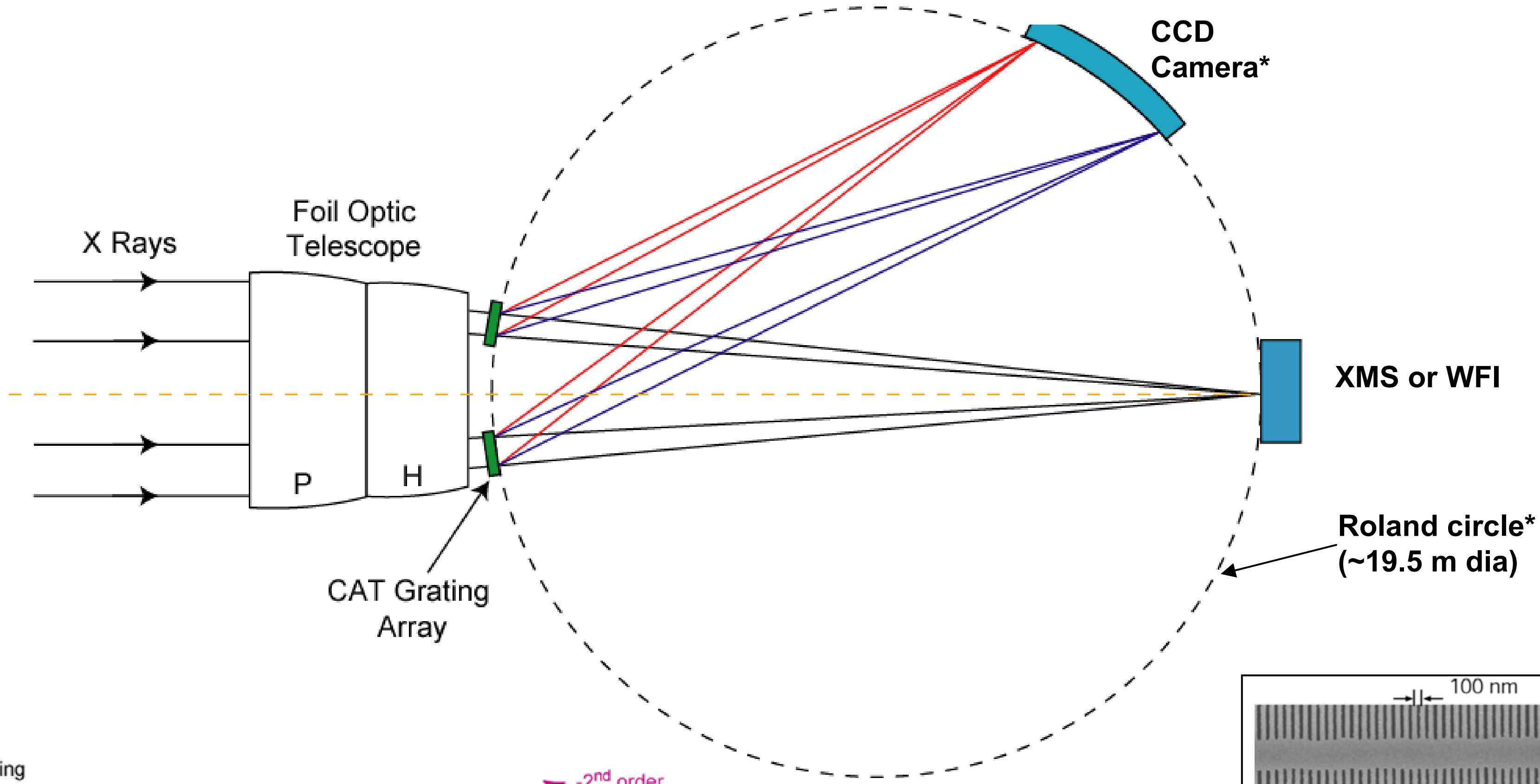
XGS

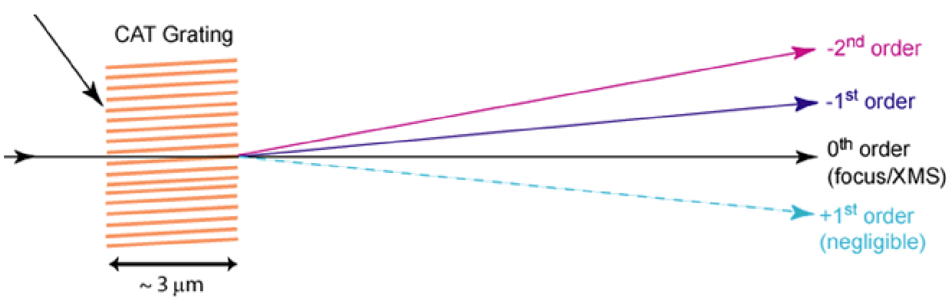
X-ray Grating Spectrometer (XGS)

- **Key Performance Requirements:**
  - Effective area >1000 cm2 from 0.3 to 1 keV
  - Spectral resolving power 3000 over full band
- **Two Grating Approaches Under Consideration**
  - Off-Plane reflection grating
  - Critical Angle Transmission Grating
- **"Critical Angle Transmission" (CAT) chosen for initial observatory study**
  - gratings mount to the aft ("exit end") of the FMA
  - Two thin grating arrays cover portion of FMA
  - Gratings have high line density (10,000 l/mm) (TBR) and are blazed:
  - Heritage from Chandra, XMM, and sounding rockets
- **CCD detector readout for the dispersed spectrum**
  - 32 CCD's in a 780 mm long array located on the fixed detector platform, 720 mm from optical axis
  - CCD's operate at -90 C to ±10 C
  - Fast readout with thin optical blocking filters
    - Readout every 0.1 seconds
  - Back-illuminated (high QE below 1 keV)
  - Heritage from Chandra, XMM, Suzaku
  - Data rate 129 kbps (ave); 1281 kbps (peak)

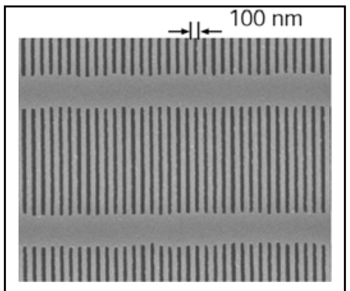


CAT (Critical-Angle Transmission) Grating Spectrometer Concept





*XGS CCD camera rotated 90 deg out of page on Rowland "Sphere"



10,000 l/mm transmission grating

XGS Mechanical, Thermal, Power Interface Requirements

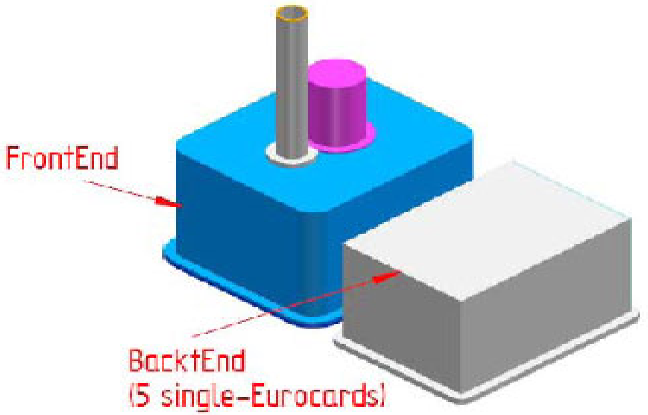
Mechanical Interface Requirements (Current Best Estimate - No Margin)				
Payload Element		**Dim (cm) H x W x D**	**Location**	**Comments / Source**
XGS	Grating Array -1	2x42.5x74.5	On FMA	H = 1, W and D = 2 modules
	Grating Array -2	2x42.5x74.5	On FMA	H = 1, W and D = 2 modules
	Sub-Total FMA			
	CCD Camera	88x24x13	On Fixed Instrument Platform	Camera only - Includes contamination door and shielding
	Detector Electronics & Mechanism Controller (DEMC)	11x11x27	< 1m from CCD Camera	Place on mirror side of FIP
	Digital Processing Assembly (DPA)	11x11x15	< 4m from CCD Camera	

Instrument Thermal Interface Requirements					
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**	**Comments / Source**
XGS	Grating Arrays	20 +/- 1 C		18 to 53C	/ Jay email 7-18-08 for operating
	CCD Camera	-30 to 10C		-120 to 70C	5 W dissipation / Tom from survival
	CCD Detector	-90 +/- 10C		-120 to 70C	
	Detector Electronics Assembly (DEA)	-30 to 10C		-30 to 55C	
	Digital Processing Electronics (DPE)	-30 to 10C		-30 to 55C	
	Power Supply & Mechanism Controller	-30 to 10C		-30 to 55C	

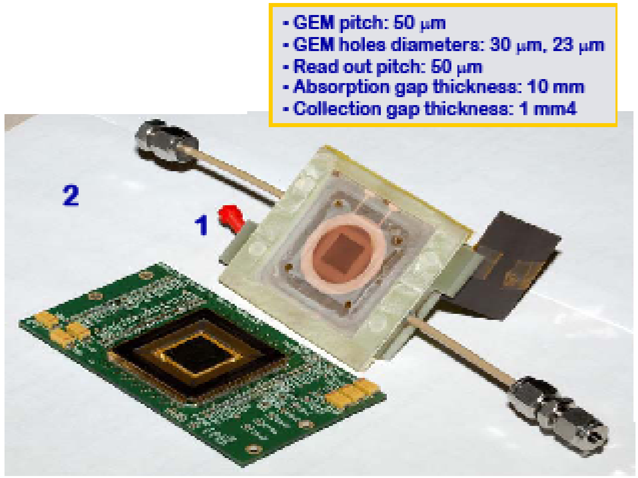
Instrument Power Interface (Current Best Estimate - No Margin)							
Instrument	**Element**	**Power (W)**					**Comments /Source**
		Average	**Peak**	**Annealing**	**Standby - Sleep**	**Safe Hold - Off**	
XGS	Grating Array-1	0.0	0.0		0.0	0.0	
	Grating Array-2	0.0	0.0		0.0	0.0	
	CCD Camera	7.2	8.6		5.0		Trim heater power
	Detector Electronics & Mechanism Controller (DEMC)	50.0	50.0		10.0	0.0	
	Digital Processing Assembly (DPA)	20	24		20.0	0.0	Space cube
	Total XGS	**77.2**	**82.6**		**35.0**	**0.0**	

XPOL

X-Ray Polarimeter (XPOL)



- **Key Performance Requirements**
  - **FOV = 2.6 x 2.6 arcmin**
  - **E = 2-10 keV, E/ΔE = 20% at 6 keV**
- **Features**
  - **Based on scintillating gas cell**
  - **Track detection gives polarization angle**
  - **300 x 352 pixels - 50 x 43.3 μm²**
  - **15.24 x 15 mm²**
  - **T_{det} = 10 C ±2 C**
  - **Room Temperature Electronics**
  - **Baffle required**
  - **Data Rate: 300.2 kbps (ave) 1000.2 kbps (peak)**
- **Interface Requirements**
  - **One detector head + FEE & back-end box on MIP**



XPOL Mechanical Interface Requirements

Mechanical Interface Requirements (Current Best Estimate - No Margin)				
Payload Element		**Dim (cm) H x W x D**	**Location**	**Comments / Source**
XPOL	Focal Plane Assembly (XPOL-FPA)	17x19x27		External baffle included
	Detector + FEE			
	Filter Wheel			
	Backend Electronics (XPOL-BBE)	19x14x11	< 20 cm (bolt together)	
	Sub-Total MIP			
	Control Electronics (XPOL-CE)	29x20x11		

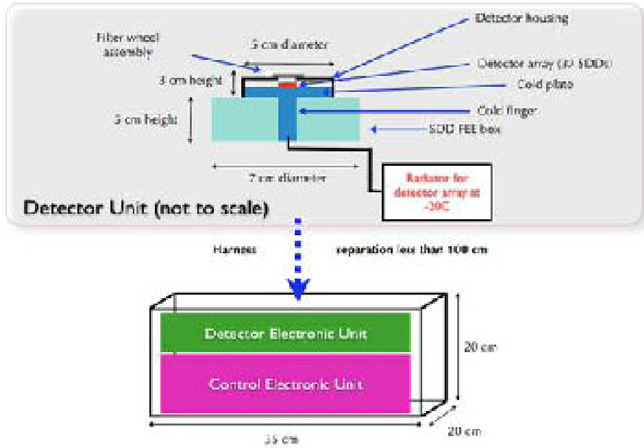
Instrument Thermal Interface Requirements					
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**	**Comments / Source**
XPOL	Focal Plane Assembly (XPOL-FPA)				
	Detector + FEE	+5 ±1 C		-15 to +45 C	Internal local heater regulator
	Filter Wheel	0C to 40C		-15 to +60 C	
	Backend Electronics (XPOL-BBE)	0C to 40C		-15 to +60 C	
	Control Electronics (XPOL-CE)	0C to 40C		-15 to +60 C	

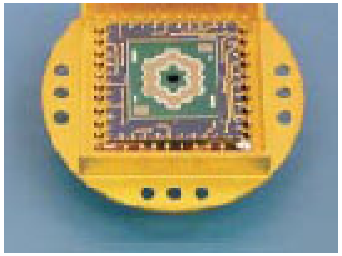
Instrument Power Interface (Current Best Estimate - No Margin)							
Instrument	**Element**	**Power (W)**					**Comments /Source**
		Average	**Peak**	**Annealing**	**Standby - Sleep**	**Safe Hold - Off**	
XPOL	Backend Electronics (XPOL-BBE)	11.7	11.7		0	0	
	Control Electronics (XPOL-CE)	34.3	34.3		0.0	0.0	
	TOTAL XPOL	**46**	**56**		0.0	0.0	

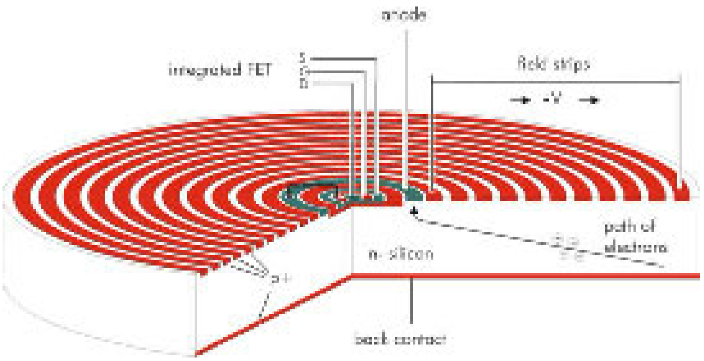
HTRS

High Time Resolution Spectrometer (HTRS)

- **Key Performance Requirements**
  - Count Rate ~ 1 Mcps
  - Resolution = 10 μs
  - Bandpass = 0.5 – 20 keV
  - Field of View: The instrument is non-imaging. Multiple pixels are used for distributing higher count-rate capability
- **Features**
  - Based on 37 silicon drift detector diodes; placed in defocused beam (182 mm)
  - Tdet = -20 C ± 1 C
  - Data Rate: 50.2 kbps (ave) 50.2 kbps (peak)
- **Interface Requirements**
  - One detector head + FEE and one electronics box on MIP
  - Baffle required – (needs to take defocusing of PSF into account)







HTRS Mechanical, Thermal, Power Interface Requirements

Mechanical Interface Requirements (Current Best Estimate - No Margin)				
Payload Element		**Dim (cm) H x W x D**	**Location**	**Comments / Source**
HTRS	Focal Plane Assembly (HTRS-DEU)	8x7dia		
	Detector			
	FEE+filter wheel			
	Central Electronic Unit (HTRS-CEU)	20x35x20		

Instrument Thermal Interface Requirements					
		Operating	**Annealing**	**Survival - (Off)**	**Comments / Source**
HTRS	Focal Plane Assembly (HTRS-DEU)				
	Detector	-20 +/- 2 C		-40 to +35 C	
	FEE + Filter Wheel	0C to 40C		-40 to +35 C	
	Central Electronic Unit (HTRS-CEU)	0C to 40C		-40 to +35 C	

Instrument Power Interface (Current Best Estimate - No Margin)							
Instrument	**Element**	**Power (W)**					**Comments /Source**
		Average	**Peak**	**Annealing**	**Standby - Sleep**	**Safe Hold - Off**	
HTRS	Focal Plane Assembly (HTRS-DEU)	22	22		0.0	0	
	Detector	20	20				
	FEE + Filter Wheel	20	20				
	Central Electronic Unit (HTRS-CEU)	34	34		**0.0**	0.0	
	TOTAL HTRS	**108.6**	**108.6**		**0.0**	**0.0**	Includes 70% eff DC-DC Conv.